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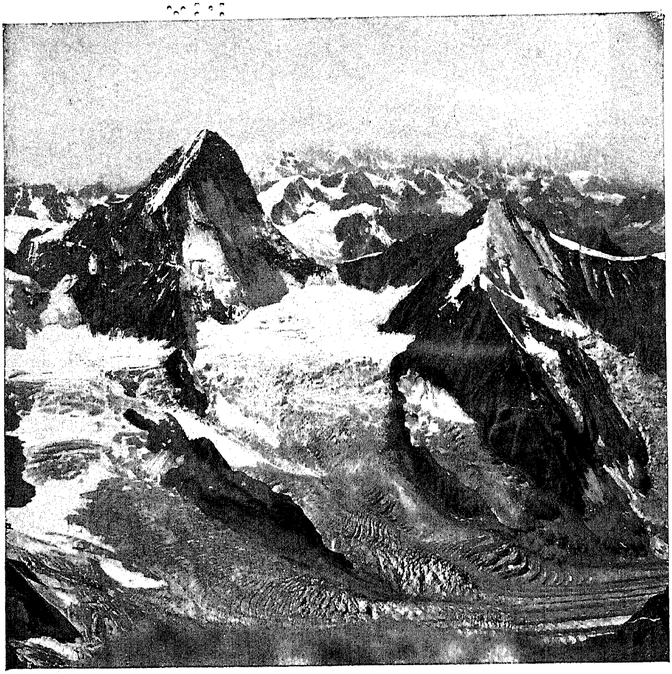

DENT BLANCHE AND THE GRAND CORNIER.

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TWO THOUSAND YEARS OF SCIENCE

THE WONDERS OF NATURE AND THEIR DISCOVERERS

BY

R. J. HARVEY-GIBSON

C.B.E., D.L., M.A., D.Sc., F.R.S.E.

EMERITUS PROFESSOR OF BOTANY IN THE UNIVERSITY OF LIVERPOOL
AUTHOR OF "OUTLINES OF THE HISTORY OF BOTANY,"
"THE MASTER THINKERS," ETC.

SECOND EDITION

REVISED AND ENLARGED BY

A. W. TITHERLEY

D.Sc., Ph.D., F.I.C.

LATE DEAN OF THE FACULTY OF SCIENCE, AND LATE LECTURER IN
ORGANIC CHEMISTRY, IN THE UNIVERSITY OF LIVERPOOL
AUTHOR OF "A LABORATORY COURSE OF ORGANIC CHEMISTRY," ETC.

WITH OVER 100 ILLUSTRATIONS

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PREFACE TO THE SECOND EDITION

In editing the second edition of this book opportunity has been taken to include a considerable amount of new matter which appeared desirable, and to remedy other defects. This has involved a very considerable expansion of the modern section, which has been largely re-written, and the incorporation of chronological and other tables which should add to the value of the text.

From the standpoint of the general reader it is unfortunate that men of science, with a few notable exceptions, should disdain to popularise their knowledge. Immersed as they are in the absorbing intricacies of their own pursuits, inspired by a disinterested and single-minded devotion to the elucidation of truth, but revelling in a complex symbolism or language intelligible only to themselves, it is perhaps hardly surprising that they have neither the time nor patience to try to get themselves understood by the world in which they live. And this world is impatient, with some justice, of the repellent terminology and bewildering formulæ which confront all attempts to understand what the outsider impolitely regards as jargon.

Simple historical treatment, such as is attempted in the pages of this book, is probably the best method of approaching and appreciating these difficulties; it indicates the laborious steps by which, in the past, man groping ever after the unattainable *ignis fatuus* of absolute truth has reached his present-day position, the foundations of which are thus exposed to view; nothing better illustrates the fallibility of the human mind than the melancholy list of discarded theories of past times, and nothing, I venture to think, exercises a more chastening influence on man's arrogance in the present.

A. W. TITHERLEY.

September, 1930.

PREFACE TO THE FIRST EDITION

SOME time ago the author was asked by a friend to recommend to him a book of reasonable size which would give him a general sketch of the growth of science from early times down to the present day, and in which he would also find an explanation, written in popular terms, of some of the principal subjects at present occupying the minds of scientific men. The author found himself unable to cite any such book save the "Short History of Natural Science," by the late Miss A. B. Buckley (Mrs. Fisher), published over fifty years ago. That work, naturally, did not include any reference to the enormous developments in science that have taken place during the final decades of the nineteenth century, and in the past twenty-five years. There are, of course, numerous books dealing with recent progress in the different branches of science, but, so far at least as the author is aware, none of a popular nature providing a résumé of the whole subject in a form suitable for general reading. The present volume is an attempt to meet that want.

The author desires to acknowledge his indebtedness to several friends who have aided him by their criticism and advice on specific points, but more especially to G. G. Chisholm, M.A., LL.D., Emeritus Reader on Geography in the University of Edinburgh; Ralph D. Given, B.Sc., Manager of the Industrial Engineering Department of the British Thomson Houston Electric Company, Rugby; A. W. Titherley, D.Sc., Ph.D., F.I.C., Dean of the Faculty of Science and late Lecturer in Organic Chemistry in the University of Liverpool; and J. Graham Kerr, F.R.S., Regius Professor of Zoology in the Uni-

versity of Glasgow. He must also express his gratitude to his friend Professor J. Joly, D.Sc., F.R.S., of Trinity College, Dublin, who was so kind as to read through the sections dealing with geology.

R. J. HARVEY-GIBSON.

April, 1929.

NOTE.—The author, Dr. Harvey-Gibson, died in June, 1929, before this book was completed, and while the early proofs were in course of revision. As one intimately associated with his work during its preparation, the melancholy duty has fallen upon me to bring the book into final shape by introducing such supplemental matter and amendments as were requisite in the interests of clearness and accuracy. But I would crave the indulgence of the public to whom this book is presented for any defects that may appear. In so vast a subject a concise and simple but well-balanced survey should be the aim; yet the story should be intelligible to readers not conversant with the mathematical and technical intricacies of Science, and must be truthful: two requirements not easily compatible in a popular exposition. This ideal has been my earnest objective in accordance with what I know was the spirit and intention of the author.

A. W. TITHERLEY.

September, 1929.

CONTENTS

TWO THOUSAND YEARS OF SCIENCE

INTRODUCTION

As we walk along a city street we observe motor-cars, waggons and tramways rushing past us but without any obvious mode of propulsion; at a seaport we watch great liners, tugboats and ferries gliding through the water without sails or oars; at a railway station we take our seats in a train and are rapidly hauled along an iron roadway to our destination, perhaps hundreds of miles away; we enter a dark room and touch a button and the room is flooded with light, although we have struck no match and lit neither candle nor lamp. The weather is inclement and we shrink from facing it to obtain something we urgently require, so we lift a receiver from an apparatus on the table and give an order to a shop perhaps a couple of miles distant. We hand in a message to a post office and within an hour or two the message is delivered in New York or Melbourne. We sit in an easy chair, with a wireless set, and we may listen to a concert being given in Paris or Vienna, or correct our watches when we hear "Big Ben" striking noon from the clock tower at Westminster. How is all this possible? Our great grandfathers never dreamt of such marvels; our grandfathers heard only whispers of some of them—wonders that are quite commonplace events to us nowadays.

We stand at the door on a cloudless night and watch the stars twinkling in the heavens, and we can tell how large they are, what they are made of, and how far distant they are from us. We see the sun rise and set, the moon wax and wane, the tides ebb and flow, and weeks, months, even years ahead, we are able to say to a minute when the sun will rise or set on a certain day, when the crescent moon will appear in the sky, and at what precise moment it will be high tide at any important harbour on the globe.

On the slabs of shale that often come to the surface from the underground workings of a coal-mine we trace the marks of leaves, stems and fruits, and of shells and skeletons of animals,

and we can explain how they came to be there. In a railway cutting or on a cliff-face we see rocks arranged in successive layers, or twisted and crumpled like sheets of paper, and we know how and when they were so laid down and what wrinkled and twisted them.

A table knife, accidentally left overnight on a lawn, rusts and becomes heavier; a strip of magnesium wire burns with a brilliant white flame; some flour mixed with saliva turns into sugar; a piece of zinc dissolves in dilute acid and gives off a gas that explodes in air when a lighted match is put to it; we pass an electric current through water and we obtain two gases, known as hydrogen and oxygen, which we can cause to reunite and form water once more.

A seed planted in suitable soil grows into a forest tree; roots bend, almost invariably, towards the earth and shoots towards the light and air; a seagull follows a steamer travelling at the rate of twenty miles an hour and keeps up with it with only an occasional beat of its wings; a caterpillar changes into a chrysalis and a chrysalis into a butterfly; man breeds new races of plants and animals for his own pleasure or profit, and masters the structure of his own body, so that he may know how to keep it in good repair and how to put it in order again should anything go amiss.

If we desire to know about all these wonderful things and thousands more, we must study science.

What is Science ?—A great naturalist and philosopher of last century—Thomas Henry Huxley—defined it as "organised common sense" or "organised knowledge." The word "organised" in the definition is important. To know that the tide ebbs and flows twice a day is a useful piece of knowledge, so also is the fact that the moon waxes and wanes and travels round the earth, as well as the fact that the earth rotates on its axis once in twenty-four hours; but before we can see the connection between these items of knowledge and their relation to other items, such as the shapes of the continents, the direction of the prevailing winds, the temperature of the air and of the ocean, and so on, all this knowledge must be organised, co-related or put in order; then only it becomes science.

Departments of Science.—The subject is so enormous that for convenience of treatment it must be broken up into departments of organised knowledge, which, however, more or less interlock. A knowledge of the heavenly bodies, sun, moon, planets, stars, comets and nebulæ, we call Astronomy; a knowledge of the structure of our own planet, of what it is made and how it came to have its present shape, we term Geology; a knowledge of the phenomena of heat, light, sound, electricity, etc., we speak of as Physics; a knowledge of the inner constitution of matter of the universe and the changes it undergoes, we call Chemistry; and, lastly, a knowledge of living things, animal and vegetable, how they live, grow and multiply, is spoken of as Biology, the science of life.

Even these departments of science are very vast, so that portions of each of them are frequently separated off, such as Mineralogy, Climatology, Meteorology, Entomology, Anthropology, and so on.

All that we now know of science was not discovered in a day, or even in two thousand years. Our ancestors, not so very long ago, knew nothing or very little of some of these sciences. They had never seen an electric lamp, a steamer, or a motorcar; they had never despatched a telegram, never spoken through a telephone, never even dreamt of broadcasting! What little they did know was often faulty and certainly was not organised; but from the very earliest times of which we have any record there have been some inquisitive philosophers who were not content merely to accept as facts what their senses revealed to them, but desired also to know the reason for them. Only when they failed to explain the earthquake, the thunder and lightning and other great mysteries of Nature, did they ascribe them to the action of supernatural agencies.

The history of science might be likened to the story of a winter bud on a tree. In the autumn it lies wrapped up in its sheltering scales,—the young leaves, axis and growing point all planned out in miniature; then follows the winter rest, when the bud lies dormant. When spring returns the bud begins to open and its leaflets peep out, daring injury and even death

from untimely frost and enemies of all kinds. At last in early summer the shoot emerges with its well-formed axis and wealth of foliage, ever progressing towards maturity, yet bearing buds in its turn, the promise of even greater developments to follow. So also in the history of science there have been four stages of growth and evolution. Long years before our era the first serious attempts at scientific enquiry began among the ancient Greeks, for the Romans had little or no curiosity about Nature and her doings. Science was then in the bud. Then came the winter of the Middle Ages, that lasted for over a thousand years, though the buds were in large measure preserved by the Arabs and the Moors. The long sleep ended, and the Fairy Prince that woke the Sleeping Beauty was the grim old monk, Roger Bacon. After struggles with stubborn foes, the young shoots began to emerge under the fostering care of Kepler, Galileo and Newton, and finally the expanded branch appeared in all its fulness in the days of Herschel, Faraday and Darwin. The buds of the future, however, show no signs of winter sleep; every day almost sees the bourgeoning of new shoots, and the tree of knowledge is growing so fast that it is beyond the power of any one brain to keep pace with its progress. The most one can do is to attempt to picture its growth as a whole, leaving the study of its individual branches to those who have leisure and inclination to follow their development.

PART I.—AUTUMN

THE BIRTH TIME OF SCIENCE

THALES— **Solstices and Equinoxes.**—We must go back very far indeed to find the name of the first enquirer into Nature's secrets; this was Thales of Asia Minor, who was in his prime somewhere about 600 B.C. He was an astronomer of high rank, for he was the discoverer of the Solstices and the Equinoxes —terms we use to this day. The sun appears to rise in the east, to sweep across the sky and set in the west, but that journey is short in winter and much longer in summer. In mid-winter the sun reaches a certain height in the heavens, and keeps on reaching the same height for several days in succession—in other words, it appears to stand still; there is a solstice, or "sun-standing." As the sun's height above the horizon at noon is not very great, we have a short day and a long night; but, as the weeks pass by, the sun rises higher and higher and remains above the horizon longer and longer, until at length it is twelve hours above the horizon and twelve hours below it. This is the time of the spring equinox, when day and night are of equal length. Upwards still the sun mounts in the sky, the day lengthens and the night shortens, until, once more, the sun keeps on reaching the same height for several days. This is the period of the summer solstice. Another three months pass while the sun gradually fails to reach its previous height, and the day and night once more become of equal length. This is the autumn equinox. Finally the sun sinks to the level it reached at the winter solstice. Of course, with a little patience, anyone can follow this cycle of solstices and equinoxes for himself, but Thales has the credit of having been the first to note and record these phenomena.

ANAXIMANDER—**Phases of the Moon.**—About once a month we have a new moon, a slender crescent in the sky, which gradually thickens until the whole surface reflects the light of the

sun, and then less and less of it shines on us until it disappears altogether. These different conditions are called the "phases of the moon," and are due to its position with regard to the sun in its journey round the earth (Figs. 1 and 2). When the moon is between us and the sun its dark face is turned towards us; when it is a quarter of its way round its orbit we see half of its surface illuminated, and when it is opposite to the sun its full face is exposed—a full moon. In this last case it might be asked how do we come to see a full moon at all? Will not the earth block off the sun's rays from it? The explanation is that the plane of the moon's orbit does not quite coincide with

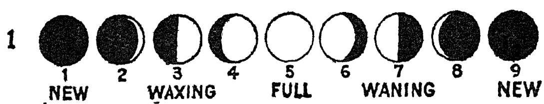

FIG. 1.—THE PHASES OF THE MOON.

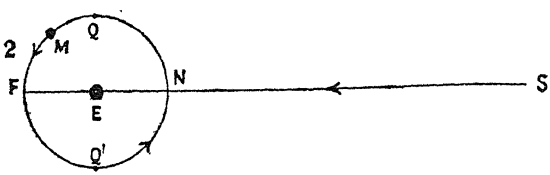

FIG. 2.—THE MOON'S PATH ROUND THE EARTH.
S, the sun; E, the earth; M, the moon; N, new moon; QQ, first and last quarters; F, full moon.

that of the earth round the sun, so that the sun's rays may sometimes pass over, and at other times under it.

All this may seem a very simple matter to us nowadays, but to the ancients it meant a knowledge, not only of the fact that the moon shines only by reflected light, but also of the fact that it revolves round the earth in about a month. These facts were discovered by a friend of Thales, called Anaximander, who was also the first to teach the Greeks how to measure time by means of a sundial.

PYTHAGORAS—**Mathematician, Astronomer and Geologist.**—Pythagoras was also a native of the Ægean coast, and lived at about the same time. In philosophy, mathematics and natural science—in all alike he excelled, but it is in his discoveries in

the last that we are most interested. He taught that the earth was a globe which revolved round a central fire; that the sea had once been land and the land had been sea; that islands had once formed parts of continents; that mountains were for ever being washed down by rivers into the ocean; that volcanoes were outlets for subterranean fires; that fossils were the buried remains of plants and animals turned into stone. These are commonplaces now in every school book on physical geography, but were very startling announcements to the Greeks, who saw in Etna the chimney of Vulcan's forge, and who believed that Olympus was the permanent abode of the immortal gods.

DEMOCRITUS—**The Atomic Theory.**—In these early days most philosophers held that the earth was composed of four elements—earth, water, fire and air; but one thinker, called Democritus, a native of Thrace, explained the structure of the universe in another way. He said that it was made up of infinitely minute particles differing from each other in size, weight, shape, etc., and that these particles were indivisible, invisible, and indestructible—" atoms," he called them, *i.e.*, particles that could not be cut in two, as the word means. At the beginning the atoms were in constant motion, but by and by they came together by chance and united in various ways to form solids, liquids and gases. Modern chemistry is founded on a somewhat similar idea, which we call the " atomic theory," although we interpret the facts differently.

HIPPOCRATES—**The Father of Medicine.**—These ancient thinkers had thus made a beginning in the study of four out of the five great sciences. There was left biology, the science of life, and it was only natural that they should commence their enquiries in that subject with the living organism that interested them most—the human body. This was done by a pupil of Democritus, Hippocrates, who has been called the " Father of Medicine." In those days ailments were thought to be inflicted by the gods, and thus the priests were obviously the appointed physicians, who made an excellent livelihood out of the offerings of the patients who came to seek relief at the shrines of Æsculapius, the god of healing. Hippocrates introduced a new system of treatment; he began by making a

careful study of the patient's body, and having diagnosed the complaint, set about curing it by giving directions to the sufferer as to his diet and the routine of his daily life, leaving Nature largely to heal herself. This was not, strictly speaking, biology as we understand it, but it was at least an attempt at the study of one living organism.

The Academy and the Lyceum—PLATO AND ARISTOTLE.—In Ancient Athens there were two great schools, or rather universities, known as the Academy and the Lyceum. The head of the former was the renowned philosopher, Plato, and of the latter, the equally famous Aristotle. With Plato we have really nothing to do, for he was not a scientific man—indeed, he might almost be said to have despised natural science. On the other hand, Aristotle, although he also ranked as a philosopher, was a keen student of Nature, and it is fortunate that so many of his writings on scientific subjects have come down to us, although in a roundabout way. The goal he set before himself was the preparation of a treatise on the whole of natural science as it was then understood, a very ambitious scheme which he carried out very unequally. His writings on what might be called the physical sciences were of little value, but those on living things, and especially on animals, were considered of great importance almost down to our own times. He was a very competent anatomist, and excelled in his descriptions of the forms and habits of animals, but he knew little or nothing of the way in which the animal machine worked—physiology—as we term the subject.

The First Botanist—THEOPHRASTUS.—Aristotle also wrote a book on plants, which has been lost, although that does not matter very much, since his pupil and successor as head of the Lyceum, Theophrastus, has left us two treatises on plants which, doubtless, contain all that Aristotle had to say on the subject. Theophrastus was a native of Lesbos, and, as a boy, studied first under Plato and later under Aristotle, whose heir he became. Attached to the Lyceum was a botanic garden in which he taught his pupils, and where he cultivated the plants whose characters and life stories he speaks about in his works. He died somewhere about 300 B.C., and with him died

the science of botany, for we do not hear of a single new discovery in that subject for over eighteen hundred years.

The Alexandrine Museum—EUCLID AND ARCHIMEDES.—A new university was meanwhile rising in Egypt to take the place of the Lyceum. This was the Museum, or Abode of the Muses, founded by Ptolemy Soter, one of the generals of Alexander the Great. To this centre of learning Ptolemy and his successors on the throne enticed as many of the great philosophers of Greece and Ionia as they could induce to settle in Alexandria, and begged, bought, and even stole every book they could lay their hands on to form the great library, which is said to have contained no less than 700,000 volumes.

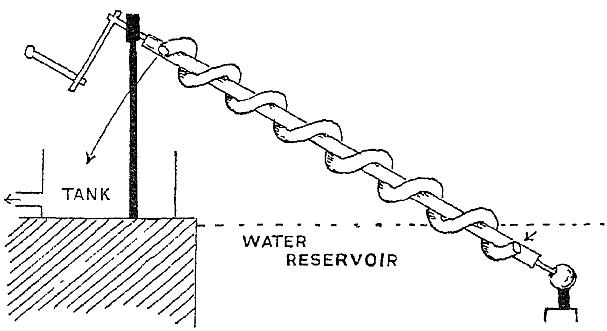

FIG. 3.—THE SCREW OF ARCHIMEDES.

One of the great scholars who migrated to the banks of the Nile was Euclid, whom every schoolboy knows as the writer of a famous book on geometry called "Euclid's Elements," but a far greater than he was Archimedes, one of the most distinguished men in the history of science. He was born at Syracuse in Sicily, 287 B.C., and studied and afterwards taught in the Museum. He was a great mathematician, and wrote on the circle, the spiral, the parabola, the sphere and the cylinder. He was the first to make out the numerical relation between the circumference of a circle and its diameter, but his best work was done in the science of physics.

He is often credited with the discovery of the lever, but what he really did discover were the laws which governed its

working. He found out also the principle of a system of pulleys, and towed a laden barge single-handed by their aid. He invented an endless screw for raising water, an apparatus still in use in some countries (Fig. 3). It consists of a tube wound round an inclined axis, one end of the pipe dipping into the water to be raised, the other opening over a tank at a higher level. The water slowly mounts the tube as the handle is turned, as if up a spiral stairway.

Specific Gravity.—One of Archimedes's most important discoveries was the law of specific gravity. It is common knowledge how he exposed the fraudulent goldsmith who was commissioned to manufacture a golden crown for Hiero, ruler of Syracuse, by estimating the amount of water displaced by equal weights of gold, silver and an alloy of these two metals, and so determining the relative amounts of gold and silver in the crown.

The Obliquity of the Ecliptic and the Precession of the Equinoxes—ARISTARCHUS AND HIPPARCHUS.—There had been several writers on Astronomy since the days of Thales and Anaximander; one of these was Aristarchus of Samos, who flourished about 250 B.C., another was Hipparchus of Rhodes, who lived about a century later. Aristarchus had learnt from his predecessors that the earth travelled round the sun, and that if one could imagine a line drawn from the centre of the sun to the centre of the earth, the latter, as it performed its annual journey, would describe a curve on an imaginary plane that was called the "plane of the ecliptic" (Fig. 4). Now Aristarchus discovered that the earth's axis, joining the north and south poles (NP-SP), was inclined to this plane at an angle of $23\frac{1}{2}°$. This was called the "obliquity of the ecliptic." Since the earth revolves round the sun once a year, the north pole will at one time be turned towards the sun and, six months later, away from it. When the earth is in the former position it will be summer in the northern nemisphere, and when in the latter

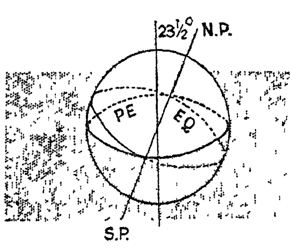

FIG. 4.—PLANE OF THE ECLIPTIC.

it will be winter, while, of course, exactly the reverse will be the case in the southern hemisphere. The intermediate positions, three months before midsummer and three months before midwinter, will be spring and autumn. In this way Aristarchus explained the succession of the seasons. Aristarchus also was the first to grasp clearly the fact that night and day were due to the earth spinning on its axis once every twenty-four hours, so that when it was light on one side of the globe it was dark on the other.

Hipparchus's contribution to our knowledge of the heavens was what is known as the "precession of the equinoxes." Consider first of all a spinning-top (Fig. 5). On watching it carefully it will be noticed that it performs two movements. first, a rapid rotation on its own axis, and, second, a much slower circular movement (*a b*) round an imaginary axis (C D) perpendicular to the ground through the point on which the top is spinning. As the speed of rotation of the top decreases this circle in space becomes larger and larger until, when the rotation has nearly ceased, the top tumbles over. It is well known that the north pole does not point exactly to the Pole Star, but to one side of it, and Hipparchus discovered that the precise spot towards which the north pole pointed was not fixed but changed from year to year, describing a small circle in space, just as the spinning top does in the preceding illustration, and he estimated that this revolution was completed in about 26,000 years. Now on looking at Fig. 4 it will be seen that this very slow movement of the pole will cause the earth's equator (EQ) to cut the plane of the ecliptic at a different point each year, and therefore that the equinoxes will never occur precisely at the same time in successive years until the circumpolar circle is complete. The change is very small indeed, not more than fifty seconds of a degree in each year, but the discovery of this forward movement, or "precession," was one

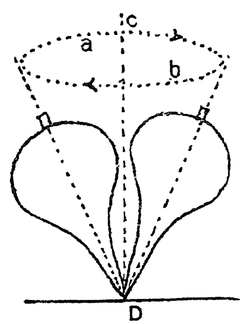

FIG. 5.—PRECESSION OF THE EQUINOXES.

of the most striking of the additions to our knowledge of the earth's motions made by the ancient astronomers. Wonder is often expressed at the remarkable acquaintance with the movements of celestial bodies displayed by the ancient Greeks and Egyptians; but it must not be forgotten that although they had no telescopes and only the crudest of instruments to aid them in plotting out the position of stars and planets in the sky, they had the immense advantage of having prolonged dry summers and clear nights, in marked contrast to what we experience in more northern latitudes.

PTOLEMY.—The last of the great men of the Alexandrine school was Ptolemy, or Claudius Ptolemæus, to distinguish him from the reigning house. He was an Egyptian, and lived in the middle of the second century of the Christian era. In spite of the fact that both Aristarchus and Hipparchus had taught in a quite convincing manner that the earth travelled round the sun, and that he was quite familiar with their views, seeing that he edited their works, it is extraordinary that Ptolemy put forward a theory of the universe of his own which was entirely erroneous, but which, nevertheless, was thoroughly believed in by the whole world, learned and unlearned, for well nigh fifteen hundred years. After weighing pros and cons, he decided that the earth was a stationary globe, and that the sun, moon and stars revolved round it. This is known as the Geocentric Theory, and it held its ground until Copernicus, in the middle of the sixteenth century, exposed the fallacies that underlay it. Ptolemy also attempted to describe the surface features of the earth itself—in other words, to write a textbook of geography. Here again he had the help of a Greek philosopher who had lived more than three and a half centuries before him—Eratosthenes.

The Measurement of the Earth—ERATOSTHENES.—Eratosthenes was the royal librarian at Alexandria, and was the first to draw parallels of latitude by the simple method of joining all the places known to him where, on a certain date, the length of the day was the same, for he rightly judged that all such places must be at the same distance from the equator. It was easy then to draw lines at right angles to these parallels and

obtain those of longitude. From this he was led to make an attempt at measuring the circumference of the earth, which he did in the following manner. Almost on the line of longitude that passed through Alexandria there was another city, Syene, now called Assouan, and he noticed that, at the summer solstice, a pillar there cast no shadow at noon, while another pillar of the same height at Alexandria did cast a shadow (Fig. 6). Now if a circle be described with a radius equal to the height of the pillar at Alexandria (A), the shadow will form a small arc on it (C D), and the length of that arc will bear the same proportion to the circumference of the circle as the distance between Alexandria and Syene (D E) will bear to the circumference of the earth. Eratosthenes found the arc was $\frac{1}{50}$ of the small circle, and that the distance between the two cities was

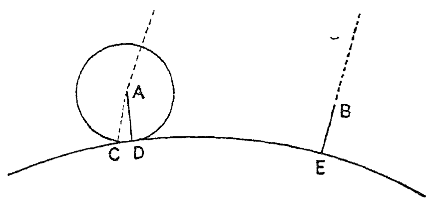

FIG. 6.—MEASURING THE EARTH'S CIRCUMFERENCE.

5,000 stadia, or, since a stadium is 607 feet, about 574 miles. Multiplying this figure by 50 gives the circumference of the earth as 28,700 miles, not a very accurate result, but not bad for a first attempt.

STRABO, **the Geographer.**—Strabo, who lived about a century before Ptolemy, was a geographer of some note. He made a map of the then known world, and, more important still, travelled over much of it and described the things he saw. Although Vesuvius was not a "burning mountain" in his day, he compared its shape with that of Etna, and said it might spring into life again, as indeed it did, some sixty years after he died, when it destroyed Pompeii and Herculaneum. Strabo had no hesitation in saying that the presence of fossil shells in rocks many miles from the sea proved that these rocks must have been formed from silt brought down by great rivers, like the Nile, to form deltas in which these animals once lived.

The Decadence of Science.—After Ptolemy's death, science in Alexandria, and indeed in the world generally, began to decay. The Romans, who succeeded the Greeks in the dominion of the world, had no taste for pure science, and those few scholars that were left contented themselves with reading and expounding the works of Aristotle and Ptolemy to their pupils, and made very few discoveries of their own.

The bud had passed into its long winter sleep.

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PART II.—WINTER

SCIENCE IN THE MIDDLE AGES

The Fall of Greece and Rome.—Ancient history tells us how the Roman Empire was overrun by the fierce tribes that invaded it from the north and east, and whom we know as Goths and Vandals. They were originally inhabitants of the almost unknown regions round the Baltic and the basin of the Vistula. In the fifth century A.D. these barbarians swept southwards, driven before the Asiatic Huns, until they became next-door neighbours of the Romans on the northern and eastern fringes of the Empire. How they at length conquered the Romans and occupied their territory is another story that must be read elsewhere. But an even greater invasion followed and completed the destruction of that great race that ruled the world from the plains of Mesopotamia to the white cliffs of Albion. In Arabia there lived originally a race of shepherds, the Arabs or Saracens. These nomads developed warlike propensities, burst into Northern Africa and overran the whole of it as far as the Straits of Gibraltar, and then passed over into Spain and Southern France. They also found their way northwards into Syria and Mesopotamia, conquering as they went, until at length they seem to have settled down and begun to devote themselves to more peaceful pursuits.

Arabian Schools of Learning.—Very soon Arabian schools of learning began to spring up in a chain round the dying Roman and Greek worlds, from Bagdad in the east through Cairo on the Nile to Cordova in Spain. The emigrants from Constantinople carried with them the writings of the Greek philosophers, and these were translated into Syriac and studied in the schools of Bagdad. From there they were handed on to Northern Africa and so found their way to Spain, where they made their appearance in a Latin version. But diligent students

of the classics as the Arabs and the Moors proved themselves to be, there were among them a few who added new fragments to scientific knowledge, and about some of these a word or two must be said.

It is difficult to say how much exactly the Arabs learnt from the Chaldeans and the Egyptians as well as from the Greeks, but one thing is certain—they studied chemistry. They had read how crude ores might be smelted and metals obtained from them. Recognising that gold was the most precious metal, many spent their lives and their riches in a vain endeavour to convert the baser metals into it, and in the course of these experiments they gleaned much information on other matters. They found, for instance, that, on heating various substances, something invisible was given off which they could collect in glass bottles, and to this they gave the name of "spirit," likening it to what they believed was the soul.

GEBER—**The Father of Chemistry.**—One of these "alchemists," as they were called, was Geber, who lived probably in the ninth century, and, if the book known as "The Summit of Perfection" was written by him, it is the oldest work on chemistry with which we are acquainted. It is full of what we would call nonsense, but it contains as well much that is novel and true. Thus, Geber showed that it was possible to separate two liquids by "distillation"—*e.g.*, by slowly heating a mixture of water and alcohol, the "spirit of wine," or alcohol, came off as a vapour at a lower temperature than that at which the water began to evaporate. This spirit could be collected and, when cooled, condensed separately as alcohol. Geber also found that he could obtain "spirits" or vapours from solids directly by the process known as "sublimation." One of the solids he experimented with was cinnabar, a red mineral which is a compound of sulphur and mercury. It is found in many parts of the world, but Geber probably obtained it from Carniola or from Hungary. On heating this substance a vapour was given off which condensed into droplets of quicksilver. This metal, which we call mercury, was known to Aristotle, and also to a famous Greek physician, named Dioscorides, who lived in the first century A.D., who called it

"hydrargyros," or "liquid-silver," or "quick-silver," the name by which it is still known in some textbooks of chemistry.

While engaged in these distillations and sublimations, Geber noticed that metals, when heated in air, gained in weight, but why they should do so he was unable to say. Indeed, it was not until nearly the end of the eighteenth century that the matter was clearly explained by the great French chemist, Lavoisier. Another of Geber's additions to scientific knowledge was his discovery of the powerful acids, nitric and sulphuric; before his day acetic acid, recognised by Pliny in vinegar, seems to have been the only acid known.

Refraction of Light and the Principle of the Lens— ALHAZEN.—While Geber was thus earning for himself the title of the "Father of Chemistry," another Arab, Alhazen, was born, who in after years made important discoveries in physics, and more especially in the subject of light. He studied the phenomena of reflection and refraction, drawing attention to the bending of the solar rays on striking the earth's atmosphere. Since the earth is enclosed in a sort of shell of air which becomes less and less dense the farther away it is from the surface, the solar rays, he said, must be bent inwards and refracted where they strike our atmosphere (Fig. 7, B C), so that when we see the sun first sinking below the horizon, it has really set some time before. We now know that that interval is about 8½ minutes.

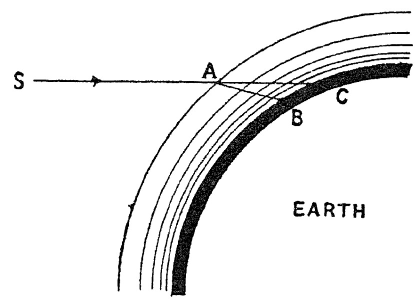

FIG. 7.—REFRACTION OF SOLAR RAYS IN THE ATMOSPHERE.

Alhazen also studied the laws governing the behaviour of a biconvex lens when it is fixed in a position to magnify any object. Suppose a small object, say a bullet (Fig. 8, B), be placed some little distance off, and a biconvex lens (L) be arranged between the eye (E) and it. When the bullet is in focus it appears greatly enlarged (B′). The rays of light reflected

from the bullet strike the lens, are bent inwards and focussed on the retina. But the eye sees all these rays not in bent but in straight lines, so that the bullet is seen magnified as at B′. It was this discovery of Alhazen's that made the manufacture of spectacles possible and led in future years to the invention of the telescope and the microscope.

Algebra and Arabic Numerals—BEN MUSA.—Although we are concerned chiefly with discoveries in natural science we must not forget entirely the growth of mathematics, and to one Arab in particular, Ben Musa, we owe the use of letters in place of figures in calculations—viz., Algebra, from an Arabic word meaning the "joining of parts to make a whole." To the Arabians or Moors in Spain also we probably owe the

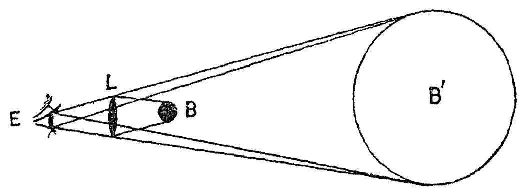

FIG. 8.—PRINCIPLE OF THE BICONVEX LENS.

introduction of what we call Arabic numerals—1, 2, 3, 4, etc.—in place of the clumsy Roman ones—I, II, III, IV, etc. The Arabs, however, did not invent these numerals or Algebra, but probably adopted them from India, and there is reason to believe that Algebra was known to the Greeks.

Thus, with the exception of Geber, Alhazen, Ben Musa and a few others whose discoveries were not of first-class rank, there are no great names on the roll of honour in all these centuries that can compare with those of the philosophers of ancient Greece and Alexandria, and after A.D. 1000 even Arabian science flickered out, and the great Moorish universities, such as those of Cordova and Toledo, disappeared altogether.

But the winter sleep was ending, and the scales that had closed over the young leaves in the bud were beginning to open. Spring was near at hand.

PART III.—SPRING

DISCOVERIES IN SCIENCE TO THE END OF THE SEVENTEENTH CENTURY

The Importance of Experimental Evidence—ROGER BACON.—There are two ways of acquiring knowledge: the first is by reading about what other people have done, the other by doing things oneself, by examining and cross-questioning Nature. She is a past master at hiding her secrets, and she will not disclose them save to those who keep on asking her.

Some who lived in the thirteenth century had begun to doubt the truth of many of the statements in the classical writings and to look askance at the explanations of natural phenomena given by the greatest writers of the past until they had tested them by experiment, and of those who lived in the years when, to keep up our simile, the bud was beginning to open, there was no one who did more to peel off the scales from it than a Franciscan monk called Roger Bacon. He must not be confused with Francis Bacon, Lord Chancellor of England, who lived about 350 years later. It is true that Lord Bacon also insisted on the importance of personal observation and experiment in all scientific enquiries, but he contented himself with telling others what to do and what not to do, without making any discoveries of his own of any importance.

Roger Bacon was a Somersetshire man, and was born in A.D. 1214. After studying at Oxford he went to Paris and devoted himself to mastering languages so that he might be able to read the works of the Greeks, not only in the original text but also in the Syriac and Arabic translations. In 1250 he returned to Oxford and began experimenting in physics and chemistry. But his studies led to his being suspected of dabbling in magic and the black arts, and he was soon recalled to Paris so that he might be under the immediate eye of the heads of the Franciscan Order. The Pope of the period, how-

ever, Clement IV., encouraged Bacon to write down the results of his labours, which he ultimately did. On his return to Oxford in 1268 he was again persecuted for his opinions and imprisoned for fourteen years, being released only just before he died.

Bacon has much to say on how to study science, and insists on the vital importance of testing by experiment every statement made by others. "Take nothing on trust" is his motto. He wrote on astronomy, and said that the earth was a mere speck in the universe and not the central feature in it as most people believed. He made an attempt at reforming the calendar, and showed how the tides were dependent on the position of the moon; but his chief work lay in the science of physics, and to what was already known he added much from his own observations and experiments. He explained the laws of perspective, and gave a quite good account of the human eye regarded as an optical instrument, and discussed the principles of reflection and refraction of light, and what a mirror and a lens do when beams of light fall on them. Although he did not actually invent the telescope, he knew that, by placing lenses in a certain position between the eye and the object, it was possible to "number the smallest particles of sand by reason of the greatness of the angle under which they appear." One of his best pieces of work was his explanation of the rainbow. He tells us that there is nothing out of the way in seeing the band of coloured light in the sky, for we can recognise the same thing in water dripping from an oar-blade, in the spray from a mill wheel, or even in the dew-sprinkled grass in the early morning. The colours are not real, he tells us, but are merely reflections of different light rays from raindrops, bent or refracted on entering the drop, reflected from its concave posterior surface and refracted again where they pass into the air on the

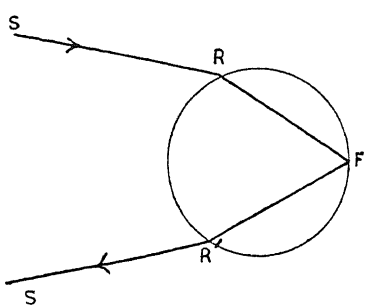

FIG. 9.—THEORY OF THE RAINBOW.

way to our eye (Fig. 9). Hence, if a hundred men stood in a row with their backs to the sun each would see a different rainbow, because each would be looking at different drops of water. In the blank spaces above and below the bow in the sky the rays, though reflected, never reach the eye at all, because the eye is not in the path of these rays.

It is often stated that Bacon invented gunpowder, but that is incorrect; he, in all probability, made it out of charcoal, saltpetre and sulphur, but obtained the recipe from some Arabian work on alchemy, some say, written by a mythical person, called Marcus Græcus. He also experimented with air, and found that a lighted candle went out when it was covered by a bell-jar, performing, indeed, the very same experiment that was made by a certain Oxford doctor, called Mayow, 400 years later. All these discoveries seem simple enough to us nowadays, but in estimating the real greatness of the thirteenth-century monk, we must always bear in mind the very credulous age in which he lived and the foolish superstitions and bigoted persecution with which he had to contend.

The Lodestone and the Compass.—For many years after Bacon's death science made very little progress; an early frost in the springtime had nipped the opening bud and retarded its growth. At the beginning of the fourteenth century, however, one notable discovery was made that was to prove of inestimable value. It is generally held that it was known to the Chinese and also to the Arabs, who doubtless learnt it from them through the eastern nations they had conquered, that a mineral existed that attracted iron. It was called "lodestone," or "leading stone," and was believed to possess magical properties. In one of the tales in the "Arabian Nights" an account is given of a ship that came too near a hill made of lodestone, with the result that the mineral pulled out all the nails from the ship's side, causing it to leak so badly that it foundered. In the early days lodestone was obtained from Magnesia in Asia Minor, and hence it came to be called "magnetic stone," from which we derive the word "magnet." It is known to modern chemists as magnetic iron oxide. Another remarkable property this mineral possessed,

and which was also apparently known to the Chinese, was that when an iron rod was rubbed with a lodestone and floated on a cork in water or suspended in air by a thread, one end of the rod invariably pointed north and the other south. Whether the Chinese actually did discover the principle of the Mariner's Compass we do not know for certain; at least, the sailors of the fourteenth century were well acquainted with it, for we read of the difficulty in getting a crew to "sign on" in any ship whose master, as they thought, steered his vessel with the aid of the evil one! Some books record that a person called Flavio Gioja was the inventor of the compass, but there are very grave doubts as to whether such a person ever existed.

The Invention of Printing.—Halfway through the fifteenth century an event took place that, although it cannot, strictly speaking, be called a scientific discovery, was destined to exert a tremendous influence not only on science but on learning in general—viz., the invention of printing from movable type. In early times pictures and writings were carved on smooth slabs of wood, so that the lines and letters were raised above the general level of the block. Over these raised lines was smeared printer's ink, and the block was then pressed on paper and as many impressions as were desired were thus obtained. But this was a slow and laborious process, so it occurred to one of these engravers, Johann Gutenberg by name, that if the letters could be made separately and of metal, it might be possible to use the same letters over and over again, combining them into words in every conceivable way. The great drawback to the old method of transcribing by hand was that only very few people could afford to buy books, and hence any discovery might take years to reach more than a very limited public. The invention of the art of printing changed all that, and, owing to the cheaper and more rapid multiplication of copies, a far wider public began to learn what was going on in the literary and scientific world.

Not long after the printing of books had become a regular industry in all the chief countries of Europe, another great event, or rather series of events, took place that led to the widening of men's knowledge on an immense scale.

The Exploration of the Globe.—Hitherto the Mediterranean had been practically the only sea of any size that had been explored. It is true some daring navigators had ventured out between the Pillars of Hercules—Gibraltar and Mount Hacho—and crept up the coasts of Spain, Portugal and France as far as our own islands, but none had dreamt of seeking unknown lands on the other side of the Atlantic. If they did, they imagined that they would merely strike the seaboard of the countries they already knew something about from their land travels in China and the Far East. The first to risk his life in this new adventure was the Genoese sailor, Columbus. The date of this memorable voyage was 1492, when he sailed from Cadiz to find the shores of "Far Cathay." He never found Cathay, but he found an entirely new continent which we call America. Fired by his example a Portuguese, Vasco da Gama, sailed round Africa and brought home word to the astronomers of the new star clusters he had seen in the southern skies. But perhaps the most adventurous voyager of all was another Portuguese, Magellan, who, early in the sixteenth century, started on the first journey round the world. After three years his ship came safely back to Seville, and thus proved once and for all that the earth was really a globe. Alas! he had not the supreme satisfaction of telling the waiting Dons of the wonders he had seen, for he was killed in a fight with natives on one of the Pacific Islands, after passing through the Straits that now bear his name.

As we have seen, science as a whole may be divided into five sub-sciences—viz., astronomy, geology, physics, chemistry and biology. We have now reached the stage when the story must also be divided into sections. It will not always be possible to keep these sciences apart, for the astronomer was often a physicist, the physicist often a chemist, the geologist both a physicist and a chemist, and the biologist a bit of all four. Advance in one science almost always means advance in another and sometimes in all; but to keep the story as nearly as possible consecutive, we will attempt to follow the progress of each science separately within the limits of certain periods of time.

§ i. Astronomy

The Heliocentric Theory of the Solar System—Copernicus.—Towards the end of the fifteenth century there was born at Thorn, on the borders of Poland, a man who was bold enough to challenge the truth of the writings of the renowned Ptolemy, not to speak of all the high and mighty philosophers, popes and bishops who regarded the earth as the centre of the universe. This was Nicolaus Copernik, or Copernicus, as he is usually styled. After his student days he became a canon of the cathedral of Ermland, of which his uncle was bishop. His canonry provided him with a salary sufficient for his wants, and as the post carried with it only nominal duties, he was able to devote himself almost exclusively to his favourite science, astronomy.

After a careful study of Ptolemy's theory of the heavens he rejected it for that put forward by Pythagoras and Aristarchus nearly 2,000 years before—viz., that the sun was the centre of the universe round which all the planets, including the earth, moved. He began his argument by showing that what had been so great a stumbling-block to Ptolemy in accepting the idea of a moving earth—the likelihood of bodies on its surface being instantly blown off it if the earth spun round on its axis every twenty-four hours—was quite imaginary, for the atmosphere and all loose objects were carried with the earth in its rotation. Again, he argued that if, as Ptolemy thought, all the stars were fixed in a gigantic globe, they must all be at the same distance from the earth, which was very unlikely. Why did they not drop out when the celestial globe was revolving at such a stupendous speed? and if the globe were solid, how did a comet manage to get through it? Of course, there were many side problems that Copernicus failed to solve, but these were satisfactorily explained by a far greater man in the years to follow—Sir Isaac Newton.

Copernicus wrote out his observations and conclusions in

a famous book "On the Revolutions of the Celestial Orbs," but it was not published until the very day of his death, May 24, 1543, almost exactly a century before Newton was born.

It was scarcely to be expected that the new theory of the universe should be at once accepted even by the astronomers, for the hold of tradition and authority was too strong. There was much spade-work to be done before the Copernican displaced the Ptolemaic theory, but in the incoming years several extremely able men appeared whose labours altered the entire outlook on astronomy. The first of these was the son of a Danish nobleman, named Tycho Brahé.

The Rudolphine Tables—TYCHO BRAHÉ.—Tycho was destined for the legal profession, and, when a mere boy of thirteen, was sent to study law at the university of Copenhagen. An eclipse of the sun, which took place in 1560, awoke in him a keen interest in astronomy, and he spent his pocket-money in buying a copy of Copernicus's book and such astronomical instruments as he could afford. Instead of burning the midnight oil over treatises on law he extinguished his lamp and started to map out the heavens from his study window. He proved himself an extremely careful observer and a skilled mathematician, and ere long he found that his own star maps did not agree with those of his predecessors. Nothing daunted, he persevered, and soon convinced himself that his instruments were at fault, and that any observations made with their aid were likely to be worthless. The obvious thing to do was to devise new ones, and the death of his uncle, who had made Tycho his heir, gave him the means of doing so.

After some years spent in Germany he returned to his native land, where the King, Frederick II., became his friend and patron, and built for him a magnificent observatory on an island in the Sound between Zealand and Sweden. This palace Tycho christened "Uraniborg," or "The city of the heavens," and there he laboured for twenty years, until the king died. The new king had no taste for learning, and was quite unsympathetic with Tycho and his work. The officers of State grudged the £400 a year that King Frederick had

allotted to Tycho as a salary, and generally made things so unpleasant for him that he was at length compelled to leave his "celestial city" and take refuge in Prague, where the Emperor Rudolph gave him another observatory, a house and a pension. It was here that he carried on the great work he had begun at Uraniborg, the making of the calculations and the compiling of the famous "Rudolphine Tables" which form the basis of the Nautical Almanacks that every sailor uses to this day. These tables were unfinished at his death, but they were completed by his assistant, an even greater man than himself, Johannes Kepler. As a practical astronomer Tycho Brahé was supreme, and yet despite his profound knowledge of the movements of the heavenly bodies, he never accepted the Copernican Theory. Nevertheless the Rudolphine Tables formed a magnificent monument to his genius, for they made possible the great discoveries of his successors.

The Laws Governing the Motions of the Planets—KEPLER.—Kepler's youth was a miserable one. His father, though of good family, was reduced to keeping a low-class tavern, in which Johannes acted as potboy, while his mother was, from all accounts, an ill-tempered shrew. He suffered much as a lad from the disease that was then the scourge of Europe, smallpox, which left him a feeble youngster, quite unfit for any heavy manual work. If his body was weak his brain was not, and this was recognised by his relations, who sent him to the university of Tübingen to study divinity. But he spent more time on the study of mathematics and astronomy than on the classics, and, when only twenty-three years of age, he was elected professor of astronomy at the Styrian university of Gratz.

While he adopted the heliocentric theory, Kepler was a firm believer in the old superstition that the planets and stars had an influence for good or evil on the lives of men, and on this extraordinary delusion was built the ridiculous pseudo-science of astrology. Poor Kepler, whose salary was barely sufficient to keep body and soul together, had to eke out his income by concocting and selling what were called "horoscopes" or charts of the stars at the times of children's births,

which were supposed to enable the astrologer to predict the events of their future lives.

During all this period he was pondering over the motions of the planets round the sun, following Aristotle in believing that, since the circle was the one perfect curve, the orbits of the planets must be circular. From his mathematical studies, he knew that the Greek geometers, since the time of Pythagoras, considered that there were only five regular solids with 4, 6, 8, 12 and 20 equal faces respectively, all their edges and angles being alike. These solids are the tetrahedron, cube, octahedron, dodecahedron and icosahedron (Fig. 10). Now in Kepler's time only five planets were known —viz., Mercury, Venus, Mars, Jupiter and Saturn —and Kepler jumped to the conclusion that the orbits of these five planets had something to do with these five perfect solids. He started with the earth's orbit as a line on a sphere and placed round it a dodecahedron whose angles gave him points on an outer sphere which was the plane of the orbit of Mars. Then he fitted round that sphere a tetrahedron whose angles gave points on the plane of the orbit of Jupiter. Outside this he placed a cube giving eight points on the plane of the orbit of Saturn. Returning to the earth he fitted within the sphere of its orbit an icosahedron which enclosed a sphere giving the plane of the orbit of Venus, and inside that again an octahedron which bounded the orbit of Mercury—altogether a very neat and ingenious demonstration. "The intense pleasure," he writes, "I have received from this discovery can never be told in words." But, alas! it was no discovery. We now know that the five regular solids have nothing to do with the orbits of the planets. Moreover, we know of eight planets nowadays, that they do not revolve in circles round the sun, and that their distances from each other do not correspond with the distances between

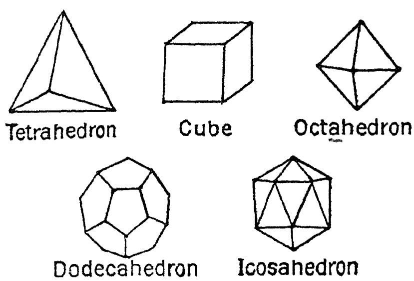

FIG. 10.—THE FIVE REGULAR SOLIDS.

Kepler's successive spheres as fixed by the angles of the five regular solids.

But Kepler's fanciful explanation of the solar system had one important outcome, for it was the means of introducing him to Tycho Brahé, whose assistant at Prague he presently became. When Tycho died the Emperor appointed Kepler his successor, and then followed a peaceful period of eight years, during which Kepler completed the Rudolphine tables. With their aid he calculated where the planet Mars should be from time to time, assuming that it travelled in a perfect circle round the sun. But Mars obstinately refused to appear where he was expected, and Kepler was reluctantly obliged to confess that if Tycho's figures were correct, Mars could not be moving in a circle at all. Then the startling suspicion arose in his mind—what if the mighty Aristotle and all the sages that followed him were wrong? Was it necessary that the planets should revolve in circles?

Kepler's First and Second Laws of Planetary Motion.—He first tried the effect of placing the sun not in the centre of the circle but in an eccentric position, and then made the planet move in its orbit, not uniformly—*i.e.*, travelling over equal arcs in equal times—but at varying rates, in such a way that it spaced out equal areas in the circle in equal times. Thus the planet would move more slowly when it was farthest from the sun and more rapidly when it was nearest to it (Fig. 11). It would thus cover the distance F E or B A in equal times but at different speeds, and the areas of the sectors F S E and B S A would be equal. Still Mars would not conform; there was something wrong with the form of the orbit. It was then that Kepler boldly discarded the idea of the circle as an orbit, for, he said, the theory must be wrong if it does not agree with the facts. He next worked through all his

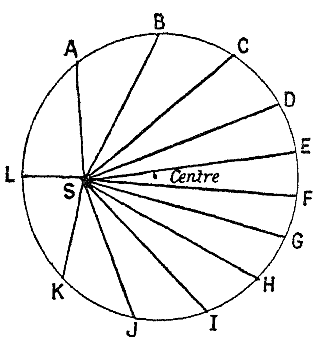

FIG. 11.—KEPLER'S SECOND ATTEMPT.

calculations again, trying ovals of various shapes, and found that, though they fitted the facts better, none of them exactly met the case. At last he hit on the ellipse, and to his joy found that if the sun were in one of the two foci all the conditions were satisfied and Mars took up his successive positions in his orbit quite in accordance with the figures. It is an easy matter to construct a diagram that will illustrate Kepler's first great discovery. Stick two pins in a sheet of cardboard, say, 1½ inches apart, and loop round them a piece of thread, 4 inches long, joined at the ends. Stretch the thread with the point of a pencil and then, keeping the thread taut, make the pencil describe a curve round the pins. The curve will be an ellipse and the two pins will be its two foci. Now imagine the sun to be in one of the foci (Fig. 12, A) and the planet at B; the line A B is what is called a "radius vector," which is continually changing in length as it sweeps round the ellipse. When the planet reaches C, the radius vectors A B and A C with the arc B C will enclose a sector B A C. Now if the whole ellipse be divided into sectors equal in area to B A C—*e.g.*, D A E and F A G—we have the key to the problem that Kepler had struggled with for so many years. He expressed his discoveries in the first two of his famous laws: (1) Planets move round the sun in ellipses, the sun being in one of the foci; and (2) a line drawn from the centre of the sun to the centre of a planet sweeps over equal areas of the ellipse in equal times.

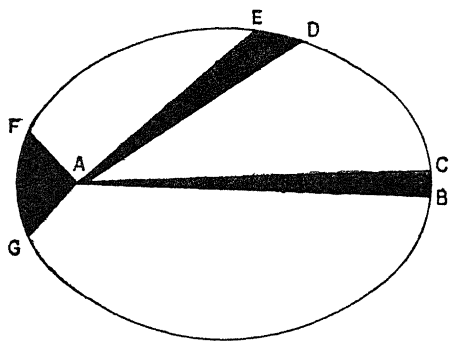

FIG. 12.—KEPLER'S FIRST AND SECOND LAWS OF PLANETARY MOTION.

Kepler's Domestic Troubles—The Third Law of Planetary Motion.—In 1612, soon after Kepler had enunciated his first two laws, the Emperor Rudolph died, and so he lost a powerful patron and friend. His salary was much in arrears,

and he had a hard fight to make ends meet. Then his wife died; three of his children sickened of smallpox, and one of them succumbed. His mother got into trouble with the courts over a law-suit, and was also accused of sorcery and condemned to the torture. Kepler hurried to her rescue, and, though he was successful in saving her from the rack, he could not prevent her from being imprisoned. Kepler left Prague and took up teaching in the little Austrian town of Linz, where he continued his struggle for a living by writing pamphlets on astrology. In spite of all these worries and anxieties, and without the aid of Tycho's observatory and his tables, he persevered with his astronomical labours, and at last was able to announce his third law of planetary motion—viz., the square of the time of revolution of each planet is proportional to the cube of its mean distance from the sun. In consequence of his discovery of these three monumental laws, Kepler has been styled "the legislator of the heavens," a title he had well earned.

Worn out in mind and body he fell ill of brain fever and died, in 1630, at Ratisbon in Bavaria, at the comparatively early age of fifty-nine.

The First Telescope—GALILEO.—Though Germany might well pride herself on having given birth to so great a mathematical genius and so skilful an astronomer as Kepler, Italy produced perhaps a greater one, Galileo Galilei, who ranks with Archimedes as one of the most illustrious scientific men the world has ever seen.

Galileo was born in Pisa in 1564, and his early training aimed at fitting him for a medical career, but he had no love for such studies, and took every opportunity of reading books on mathematics and physics. In the end he had his own way, and progressed so rapidly that when he was only twenty-six years old he became professor of mathematics in the university of his native city.

During the early years of the seventeenth century the first telescope had been invented by a Dutch spectacle maker called Lippershey. Galileo was quick to see the value of such an instrument in astronomy, and at once set about making a better one for himself. It was, after all, a poor affair, for it was

made out of a small organ pipe with a lens at either end (Fig. 13). The lens (O) received rays (S) from any distant object, and brought them to a focus at F, while an eyepiece (E P) magnified the image and transmitted it to the eye (E).

Galileo had studied Copernicus's great work and was familiar with Kepler's laws, and so had no doubt in his own mind that the sun and not the earth was the centre of the solar system. His other discoveries, which had to do with

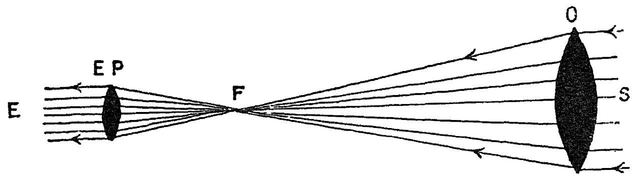

FIG. 13.—PRINCIPLE OF THE TELESCOPE.

physics, had brought him into trouble with the clergy and the learned men of Pisa, so he left that city and accepted a professorship in Padua in the free republic of Venice, where he remained for eighteen years and where much of his work was done.

Having made his telescope, he turned it on to the moon, and showed to his astonished friends its mountain ranges, its ravines and extinct volcanoes. He found that Venus and Mercury went through phases, just as the moon did, and

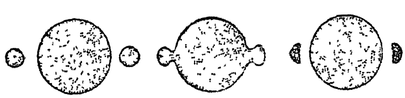

FIG. 14.—GALILEO'S IMPRESSION OF SATURN'S RINGS.

demonstrated to his pupils that the Milky Way was composed of thousands upon thousands of stars. He gave offence to many of his colleagues by finding spots on the sun, and said that it revolved on its axis once a month. He discovered also that the planet Jupiter had four moons, although some of his hearers refused even to look through his telescope lest they should see them! But the telescope also showed that, as he thought, the planet Saturn, moving in an orbit far outside

that of Jupiter, was sometimes triple, and at other times single with two great knobs, one on either side (Fig. 14). Later on, in 1610, he found that Saturn appeared to be single once more. How these changes came about was explained half a century afterwards by the Dutch astronomer, Huygens, of whom we shall speak by and by.

The Persecution of Galileo.—All these discoveries were exceedingly distasteful to the followers of Aristotle and to the clergy. So long as Galileo remained in a city under the Venetian Republic he was safe from persecution, but on an evil day he accepted an invitation to become astronomer to the Duke of Tuscany, and now being a resident in papal territory he became liable to be questioned by the Inquisition. He had approved and taught the theory of Copernicus in Padua, and he now boldly restated it in Florence; but Florence was not Padua. Copernicus's work, on the "Revolution of the Heavenly Bodies," had been condemned in 1615 and placed on the index of forbidden books, and of course Galileo, by teaching what it contained, was defying the papal edict. He was called to Rome and there ordered not to teach the Copernican system. As argument with his judges proved of no avail; he returned to Florence, where he lived peacefully for seven years.

A new pope, who, as a cardinal, had befriended Galileo, came to the throne, and Galileo pleaded with him to lift the ban that had been passed seven years before, but the appeal was unsuccessful. Then Galileo did a foolish thing: he published "A Dialogue of the Two Systems of the World," in which he made an imaginary supporter of Ptolemy and a supporter of Copernicus argue the matter out, with what result may easily be imagined. The Ptolemaic philosopher was made to look like a fool. Some evil-minded person persuaded the pope that "Simplicio," as the supporter of the Ptolemaic system was called, was meant to represent the pope himself. Again Galileo was summoned to Rome, and this time was made to recant publicly everything he had believed and taught. He was then banished to a house near Florence, where he lived, virtually a prisoner, for nine years. In addition to constant

illness he became blind, so that he could no longer explore the starry heavens, but gave himself up to the study of physics instead, in which subject he made even greater discoveries than those he had done in astronomy. He died in January, 1642.

The Transits of Mercury and Venus—GASSENDI AND HORROCKS.—Between the earth and the sun there are two planets, Venus and Mercury, the latter small and nearer the sun, the former nearer us. These bodies are also revolving round the sun, but much more rapidly than we are, for Mercury completes his journey in eighty-eight days and Venus in two hundred and twenty-five. Both of them in this way may cross the face of the sun from time to time, and these crossings are called "transits." But since the orbits of these two planets are not quite on the same plane as that of the earth, these transits cannot always be observed, for the planets may pass either above or below the sun's disc as seen by us. In the case of Mercury a visible transit may happen at intervals of seven or fifteen years, but in the case of Venus much more irregularly. Two transits of Venus succeed each other at an interval of about eight years, and then no transit occurs for more than a hundred years. A transit of Mercury was first observed by the French astronomer, Gassendi, in 1631, and the first transit of Venus by a young Liverpool man named Horrocks, in 1639.

The Size and Distance of the Sun—HALLEY.—The observations of these transits were in themselves very interesting, but they were supremely important for another reason; for it is by their means that we are able to measure the size of the sun and estimate the distance it is away from us.

At transit Venus is about two and a half times as far from the sun as she is from the earth, and the sun's distance from us is something like 108 times his diameter; what then is the diameter of the sun's disc?

Draw two parallel lines, and unite them by a line at right angles (Fig. 15, E S). Divide E S into seven equal parts; mark a point, V, midway between E and S, and fix on any two points, A and B, equidistant from E. Join A V and continue the line to C, and draw B V D in the same way. Of course, C D will be equal to A B, and the spots C and D will

be invisible from A and B respectively, since V comes in the way. Shift V to the fifth mark from S, then V′ will be two and a half times as far from S as it is from E, and if the lines A V′ G and B V′ F be drawn, the distance F G will be two and a half times A B. If V′ represent Venus, an observer on the earth at A will see it as a black spot on the sun's disc at G; another observer at B will see it as a black spot at F, and if the distance A B be known, F G may easily be calculated. The moving planet traces a line across the sun's disc, but an observer at A will see a different track from that seen by an observer at B. If the two observational points be separated by the whole diameter of the earth, approximately 7,900 miles, then the distance from the track seen by A and that seen by B will be 19,750 miles. If the distance between the two tracks be $\frac{1}{44}$ of the sun's apparent diameter, we get 869,000 as the sun's actual diameter in miles, and if the mean distance of the sun from the earth be 108 times its diameter, that distance will be 93,528,000 miles. Of course, these figures are far from accurate, and no account has been taken of a number of factors which modify the result, but they may serve to show how the actual measurements were first made.

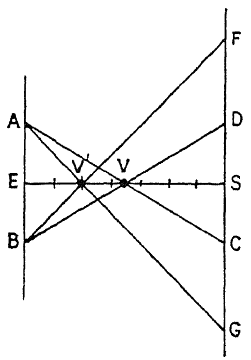

FIG. 15.—THE SIZE OF THE SUN. (See Text.)

This method is due to the astronomer Halley, who travelled to St. Helena in 1676 to map out the constellations of the southern skies. In that lonely little island in the South Atlantic he observed a transit of Mercury, and it was there that it occurred to him that the distance of the sun might be calculated from the time taken by a planet to cross the sun's disc. As Mercury was too far off he suggested Venus, but, unfortunately, there was to be no transit of Venus for eighty-five years, so that Halley could not possibly observe it. He succeeded, however, in persuading the Royal Society to undertake the task when the time came. This they did, and the observer sent to the Pacific was the celebrated Captain Cook. The transits

of 1874 and of 1882 were also carefully observed not only by British astronomers but also by those of other nations. In all probability there are few now born who will see the next transit of Venus, which will not take place until 2007.

The Periodicity of Comets.—With Halley's name we associate another celestial event. Comets used to be regarded as casual wanderers that sometimes paid us visits and then disappeared into space, never to return; but Halley studied, very carefully, the comet that appeared in 1682, and consulted the records of previous visits of a similar celestial vagrant, and found that one like it had paid us a call every seventy-six years. He boldly predicted that it would return in 1758, and back it came, although Halley was not alive to see it. Halley's comet reappeared in 1834 and again in 1910, and it will almost certainly pay us another visit in 1986.

Sir Isaac Newton.—In the history of science we meet with the names of many great men, but all will admit that one of these stands out pre-eminent, that of Isaac Newton. He was the posthumous son of a small farmer in Lincolnshire, and was born in 1642, the year Galileo died. He took no interest in crops and cattle, so that after his mother's remarriage his uncle took charge of him, and in due course sent him to the university of Cambridge, where he studied mathematics. It is recorded that he had no patience with Euclid and threw it aside as a "trifling book," but he tackled a much more difficult one on geometry written by the famous French philosopher, Descartes. Even this did not satisfy him, for he discovered what are nowadays called the "Binomial Theorem" and the "Differential and Integral Calculus." These great mathematical works alone would have made Newton's name famous for all time, but there was more to follow.

The Law of Universal Gravitation.—In 1665 the Great Plague broke out, and the university was closed, so that Newton had to return to his home at Woolsthorpe, a few miles from what is now the great railway junction of Grantham, and there in the quiet country he meditated on the revolutions of the planets round the sun. Why did they revolve at all, and what kept them in their orbits? Had gravity anything to do with

it? So far as any article near the earth's surface was concerned, he knew that the force of gravity acting on any falling body increased its velocity by 32 feet per second every second. Thus a body released at a certain height acquires velocity due to the force of gravity, such that at the end of the first second the velocity is 16 feet per second. Newton asked himself would the same law apply to bodies in the heavens moving at vast distances—the moon, for instance? The moon, he knew, was distant from the earth's centre sixty times the earth's radius, and if sixty miles made one degree, and since there were 360 degrees in a circle, the radius of the earth would be about 3,436 miles. Hence the moon was 206,160 miles distant, and the force of gravity must be $\frac{1}{3600}$ of what it is on the earth's surface, because the force of gravitation is inversely proportional to the square of the distance from the earth's centre—*i.e.*, taking the distance at the earth's surface as 1 the distance of the moon is about 60 and $\frac{1}{60^2}=\frac{1}{3600}$. Newton's problem was: Is the force of gravity sufficient to pull the moon towards us with an acceleration of $\frac{1}{3600}$ of the above 32 feet? If so it is easy to see the earth should pull the moon at the rate of 16 feet in a minute, but it did not—the figure was only 13·9. There must be something wrong with the theory for, after repeated trials, he found that his calculations were absolutely correct. Although he did not solve the problem till sixteen years had passed, and had not mentioned the subject to anyone during all that time, we may as well complete the story now. At a meeting of the Royal Society in 1682, Newton heard that a Frenchman, named Picard, had made a new measurement of the earth, and found that a degree worked out to 69·1 miles, and not 60, as everyone had hitherto believed. This, of course, made the earth considerably larger, and raised the length of the radius. Newton at once went over his old calculations in the light of Picard's figures, and to his joy the result came out exactly right—the attraction of the earth was the guiding force on the moon.

Now that the principle was discovered, it followed that not only did the earth attract the moon and the sun the earth, but every body in the universe attracted every other body inversely

as the square of the distances separating them. The Newtonian law of Universal Gravitation—one of the greatest scientific discoveries ever made—is thus enunciated in Newton's own words: "The gravitational force acting between two bodies is inversely proportional to the square of their distance, and directly proportional to the product of their masses."

The Tides.—Newton's law had far-reaching results. For many centuries it had been known that there was an intimate

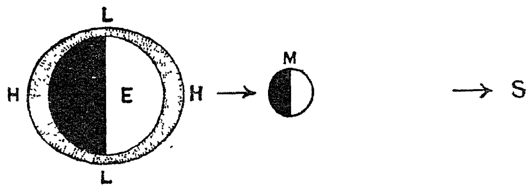

Fig. 16.—Spring Tides.

connection between the tides and the moon. The high tides were highest when the moon was either new or full, and lowest when it was in its first or last quarter. The explanation was now simple. Both sun and moon attract the mobile ocean, and when both attract it at the same time in the same direction there will be high or "spring" tides, but when the sun is pulling one way and the moon is pulling at right angles to the sun, the tides will be "neap" (helpless). In Fig. 16, E represents the earth, surrounded by a layer of water covering its whole surface. M and S represent the moon and sun respectively. Both earth and moon face the sun, and the moon is "new."

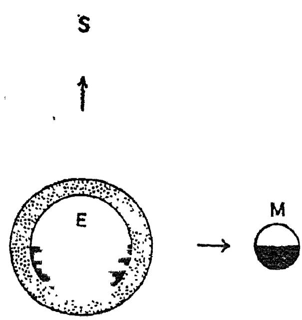

Fig. 17.—Neap Tides.

Both sun and moon are pulling on the ocean at the same time and in the same direction, causing it to bulge out at H H—*i.e.*, high tide—and lessen its thickness at L L—*i.e.*, low tide. In Fig. 17 the sun is pulling at right angles to the moon, which is now in one of its quarters. Both have a pulling

effect on the ocean, but the moon being very much nearer has the greater power, so that the high tide is not quite so high and the low tide not quite so low, since the sun in part neutralises the stronger effect of the moon. The matter is, of course, nothing like so simple as this when details are considered, for in determining the tides exactly we have to take into account many other factors, such as the distribution of sea and land, the temperature of the water, the prevailing winds, and so on.

The Cause of the Precession of the Equinoxes.—The Greek philosopher, Hipparchus, more than 100 years B.C., noted that the north pole of the earth was describing a small circle in the heavens round the Pole Star, and estimated that it took about 26,000 years to complete it. Hipparchus knew nothing more than the bare fact, but Newton gave the reason for it. A model will help to make the explanation clear. In Fig. 18, A is a fine steel ribbon welded into the form of a circular band, and fastened at what we may call the south pole to a small pulley-wheel, D. Springing from the centre of D is a rod, B, which pierces loosely the ribbon at its north pole, so that the north polar region may be pushed down the rod, becoming a circle again when the pressure is withdrawn. The whole apparatus may be made to revolve by means of the larger pulley-wheel C. If the pivot be made to revolve rapidly, the north pole of the ribbon will begin to descend, all the more so the more rapid the rotation. As a consequence the circular ribbon begins to bulge out at its equator and flatten at the poles (A′); it ceases to describe a sphere, but, instead, a spheroid. Since the earth spins round on its axis it is not an exact sphere but a spheroid, being flattened at both poles. Probably this flattening was greater thousands of millions of years ago when the earth spun more quickly, but it still retains its spheroidal shape. Actually the diameter of the earth at the equator is twenty-eight miles longer than that joining the

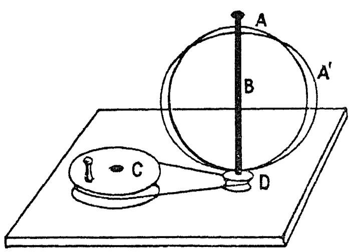

FIG. 18.—SPHERE AND SPHEROID.

poles. The planet Jupiter is much more spheroidal than the earth, for his equatorial diameter is approximately 89,000 miles, while his polar diameter is about 84,500 miles. Possibly Jupiter is still in a semiplastic condition, and it is rotating much more rapidly than the earth, spinning on its axis once in ten hours. Now a sphere attracts as if its whole mass were at its centre, but a spheroid does not; in other words, the moon does not pull through the exact centre of the earth. If a top be spun on its axis, the axis will presently begin to describe a cone which will be all the more marked as the speed of rotation decreases (Fig. 5). Newton made the calculation for the rotating earth, and found it to be just what was required to account for the precession of the equinoxes.

"The Principia."—Newton incorporated these and other brilliant discoveries in a book called "The Mathematical Principles of Natural Philosophy," commonly called "The Principia." A genius so great as Newton did not take kindly to the preparation of such a book for the press, but he had an ardent admirer and friend in the astronomer Halley, who undertook the task and carried it to a successful conclusion, paying the printer's cost out of his own pocket.

A few years after the publication of the "Principia," and when he was yet in his prime, Newton seems to have given up scientific research and devoted himself to work connected with the Mint and the new coinage then being issued. He also amused himself with alchemy, hieroglyphics, and biblical prophecies, but the stars knew him no more. (His discoveries in physics we shall consider later on.) He died in 1727 in his eighty-fifth year.

§ ii. Geology

During the long night of science people took little or no interest in what was happening either inside or outside the earth's crust, and those who did pay some attention to such matters were afraid to write about them because the facts, as they saw them, clashed with the teachings of the Church.

The story of the creation told in Genesis was taken literally, which meant that the earth was made in six days, and was not more than 6,000 years old. Fossils gave the greatest trouble, and all sorts of fanciful explanations were put forward to account for them. Some said they were mineral secretions, others that that they were "freaks of nature," but the favourite theory was that they were the remains of animals that had been drowned in Noah's flood, although how fishes and marine shells came to be "drowned" seemed to want some explaining.

Leonardo da Vinci.—There was one man, however, who studied the subject in the spirit of Roger Bacon, and that was Leonardo da Vinci, who lived in the end of the fifteenth century. It is very difficult to give in a few words an adequate picture of this very remarkable man. Perhaps he is best known as a great artist, for every one has heard of his famous pictures, "Mona Lisa" and "The Last Supper." But he was an inventor of great ingenuity also. He made water wheels, paddle wheels, breech-loading cannon, mining machinery and endless other appliances. He worked at magnetism, at steam as a motive power, and even studied the circulation of the blood. He held that the earth moved round the sun, and thus really forestalled Copernicus, and made many discoveries in optics, gravitation, friction, heat and light. He was also a distinguished engineer, and it was while superintending the cutting of canals in Northern Italy that he came on rocks crowded with fossils. Using his common sense he made fun of the idea that these were either "freaks of nature" or the remains of Noah's flood, and said the shells had once lived on the sea, and had been buried by silt washed down by rivers from the hills. All this was perfectly true, but such views could not overcome the prejudice of people of the fifteenth century, who preferred to believe what their fathers had told them rather than the evidence of their own senses.

Steno.—There were a few exceptions in this unscientific age, and one of these was Nicholas Steno, the Dane, who was a contemporary of Newton. He began his career as a physician, and settled for a time in Florence, where he wrote his treatise on "Solids enclosed naturally within solids." He saw that

the layers, or, as we would call them, strata that form the crust of the earth, are like pages in a book, telling us of events that took place many years ago. He showed how rivers carved out valleys, and incidentally created mountains, and gave a very fair account of what came to be called the "Denudation Theory." It is true he still believed in the old notion that volcanoes are due to enormous subterranean fires, resulting from the combustion of substances containing carbon. But all through his book we can see how he hesitates to draw the obvious inference as to the immense age of the earth, and as a Catholic bishop, which he ultimately became, he dared not say that the earth was more than 6,000 years old, or that fossils were anything else than the remnants of animals that lived at the time of the Flood.

Although they were not strictly speaking geologists, there were some men, who lived in the seventeenth century and the early years of the eighteenth, who speculated on how the earth came into existence. These were men like Descartes, the mathematician, the philosopher Leibnitz, and the naturalist Buffon, but it would scarcely be worth while to spend time over what were largely guesses. Geology had a long way to travel before any speculations as to the origin of the earth could be made that were based on the facts which the earth itself disclosed. The collection of these facts was the task of the geologists of the eighteenth century, and of the men who gathered them we shall learn in due course.

§ iii. Physics

The science we have now to study is physics, comprising the laws which govern the movements and states of matter, the nature of heat, light, sound, electricity, and so on. This is an immense subject, and we owe much of our knowledge of it to men who were at the same time great astronomers, like Galileo and Newton.

The Foundations of Electricity—Gilbert.—We have already seen that in the beginning of the fourteenth century

people were acquainted with a mineral called lodestone that had very peculiar properties, which were made use of in devising the mariner's compass. More than 250 years afterwards, an Englishman named Gilbert made some discoveries that were the beginnings of a branch of physics that was destined to revolutionise the world in days to come—electricity. Gilbert was a physician, practising in Colchester, who took a great interest in this subject. He knew that a piece of amber, or fossil resin, after being rubbed with a soft cloth, could attract feathers, scraps of paper, or any other light objects, but he discovered also that it was not amber only that had this power; sealing-wax, jet and many other substances acted in the same manner, and he noticed that the power of attraction they possessed was much greater when the air was dry and cold than when it was wet and warm. The Greek word for amber is "electron," and it is from this word that we derive the title of this branch of physics, viz., "electricity."

The Principle of the Pendulum—Galileo.—Great as were Galileo's services to astronomy, some hold that his discoveries in physics were even greater, and to some of these we must now direct our attention.

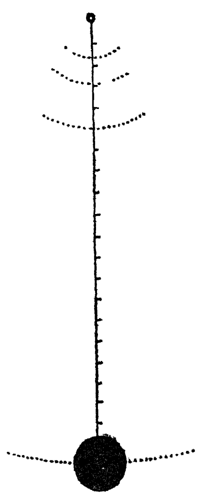

Fig. 19.—Principle of the Pendulum.

There is the oft-told story of his having been at a service in the cathedral at Pisa, and of his having noticed the swinging of one of the lamps hanging from the roof. He counted the number of swings, using his pulse as a time measurer, and soon saw that the lamp took the same time to swing in a small arc as in a larger one. He then began to experiment on the subject and discovered the law of the pendulum.

Suspend a disc of metal by a thread so that it may swing free (Fig. 19). If the thread be about 40 inches long the pendulum will beat seconds. If it be desired that it should beat twice in a second, how long must the thread be? One would naturally imagine 20 inches, but it is not so—the thread must be only a quarter of the

length, *i.e.*, 10 inches; if three times a second $\frac{1}{9}$ the original length, or $4\frac{4}{9}$ inches; if four times a second $\frac{1}{16}$ or $2\frac{1}{2}$ inches, and so on. From these figures we get the law of the pendulum, "the length of the thread is inversely proportional to the square of the number of beats in a given time." Thus twice the beats, $\frac{1}{4}$ or the inverse of 2^2, $\frac{1}{9}$ or the inverse of 3^2, $\frac{1}{16}$ or the inverse of 4^2, and it is on this principle that our modern pendulum clocks are regulated.

The Law of Falling Bodies.—Galileo's next discovery got him into trouble with all the learned people who thought that Aristotle was, if not inspired, at least very nearly so. Aristotle had said that a heavy weight fell to the ground more rapidly than a lighter one. If a penny and a sheet of tissue-paper be dropped from the same height at the same moment, the penny reaches the ground first, but that is because the penny is only slightly buoyed up by the air, since it has a small surface as compared with its weight, while the paper exposes a large surface to the air, and has a very small weight. If both be placed at the top of a long jar from which all the air has been extracted by an air pump and both be released at the same moment, they will reach the bottom of the jar together.

Galileo had no air pump, for that instrument was not invented till several years afterwards, but he performed a notable experiment on a large scale. He took two weights, one of 100 pounds and another of 1 pound, and carried them to the top of the famous Leaning Tower of Pisa. This Tower is 179 feet high and overhangs its base by $16\frac{1}{2}$ feet, so that there is a clear drop from top to bottom. He released the two weights at the same moment, and they struck the pavement simultaneously. One might imagine that this experiment would have convinced those who watched it that Aristotle was wrong. Far from it; they had their classics, written by the renowned sages of antiquity, which had served the learned of all nations for nearly 2,000 years, and why should they now throw over these classics because an unknown youth, who had begun life as a draper's assistant, had dared to contradict writings almost as sacred as the Scriptures themselves? So Galileo left the Pisans to their

dreams and went, as we have seen (p. 31), to become professor in the university of Padua, and his subsequent history we have already traced.

After Galileo's banishment to the Villa Arcetri, near Florence, he became blind; but, not discouraged by this calamity, he spent his declining years in studying the laws that govern moving bodies, the discovery of which was quite enough to have made him famous for all time.

The Laws of Motion.—If a moving body, he said, is not acted on by some force, it will continue to move for ever at the same rate and in the same direction in which it is moving. If a stone be thrown into the air, and if it be not interfered with in any way by any other force, it will fly off into space with its initial velocity and at the same angle; but since, instead of doing so, it begins to move more and more slowly and gradually sinks to the earth, some force or forces must be interfering with its free movement. First, it encounters the resistance of the air which reduces its speed, and, second, it is drawn down towards the earth by the force of gravity, and thus its direction is changed. Once a body is put in motion it requires no force to keep it going. So a planet moving round the sun continues to do so, but its pathway is always changing owing to gravitation exerting a pull on it towards the sun's centre.

Galileo's second law is that when a moving body is acted on by any force, the movement alters either in rate or direction or both, in proportion to the force exerted and in the direction in which the force is applied. If a bowler serves a loose ball at a certain speed to a batsman, the latter may hit it to leg for four; the batsman has changed the direction and the velocity of the ball by applying a new force derived from the muscles of his arms transmitted to the bat. Had he not so diverted it and at the same time given it an extra jog, and if the wicket-keeper did not stop the ball, it would have come to rest in the grass, many yards away, when the friction of the air and of the grass had overcome its initial velocity.

The third law is the easiest of all to understand, and is familiar to everyone; it is merely this—action and reaction

are equal and opposite; that is so obvious that it needs no explanation. It was really these three laws and Kepler's laws that enabled Newton to build up his theory of universal gravitation.

The Barometer—TORRICELLI.—One of Galileo's most distinguished pupils was Torricelli, who became professor of mathematics at Florence, and who was permitted to visit his master in what was really his prison. After Galileo's death, in 1642, Torricelli managed to secure some of his papers, among them those that dealt with the laws of motion. He smuggled them out of Italy and had them printed in Holland, where there was no inquisitorial censor. One manuscript contained notes on a problem that Galileo had failed to solve. He had found that he could pump water up to a height of about 33 feet, but that it obstinately refused to rise any higher. It was this problem that Torricelli tackled. He argued that if air had any weight then it must press equally on the surface of the water outside and inside the tubular shaft; but if, by the aid of an air pump, the air could be removed from the inside of the shaft, the water should rise until the column equalled in weight the air pressure outside. Torricelli found that it took about 34 feet of water to equal this atmospheric pressure, which he estimated to be about 15 pounds on the square inch.

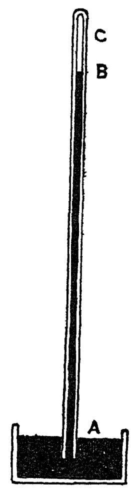

FIG. 20.—PRINCIPLE OF THE BAROMETER.

Torricelli next used mercury instead of water, and, knowing that mercury was fourteen times as heavy as water, he argued that it should rise only $\frac{1}{14}$ of the distance that water did—viz., between 29 and 30 inches. He then took a glass tube about 3 feet long (Fig. 20), closed it at one end, and filled it with mercury and, covering the open end, inverted it in a basin filled with the same liquid metal. The mercury fell in the tube to B, about 30 inches above A, leaving the space, C, quite empty. Now it is obvious that if the air becomes heavier than normal it will exert greater pressure on the surface at A, and hence force the mercury further up into the empty space, C; and

conversely, if the outside pressure decreases the mercury in the tube will fall. It is on this principle that the mercury barometer is constructed. It is well to bear in mind that that instrument does not foretell the kind of weather to be expected in the immediate future; it indicates only the weight of the air pressing on the outside mercury. But as the air varies in weight according to the type of weather and the amount of moisture it contains, we are able to deduce the kind of weather we are likely to have. The rise and fall of the mercury may be observed directly and measured by an attached scale, or its movements may be communicated by transmitters of various kinds to the index finger of a dial.

There is another use to which the barometer may be put. We have seen that the atmosphere forms a sort of envelope over the earth, which is believed to be anything between 200 and 500 miles thick. It is naturally densest at the sea level, but becomes gradually more rarefied upwards. At a height of 3¼ miles it is only about half as dense as at the surface, and at 7 miles only a quarter. Hence the difficulty in breathing experienced by climbers of lofty mountains such as Mount Everest, which is 5½ miles high. It is obvious that if a barometer be taken up a high mountain the height may be estimated by observing how low the mercury sinks in the tube. As a mercury barometer is an awkward instrument to carry up a hill, another kind, invented long years afterwards and called an aneroid, is now used. It depends on the pressure of air acting on an empty aluminium drum, but we need not go into its construction here, and it did not come into use until the middle of the nineteenth century.

The Thermometer—DREBBEL, FAHRENHEIT, CELSIUS.—Although Galileo is often said to have invented the thermometer, or measurer of temperature, his instrument was not of much value. A much better one was devised by a Dutchman called Drebbel, who also invented the first submarine. Drebbel used spirits of wine in his thermometer, and such instruments are still employed; but by far the commonest type is the mercury thermometer (Fig. 21). It is made by taking a glass tube of very fine bore ending in a bulb and filling it with

mercury for a certain distance up the tube, the end of which is at first open. The mercury is then heated, and as it expands it rises in the tube, driving all the air out. The tube is then hermetically sealed by fusing the open end. As the mercury cools it contracts, and, in falling, leaves the upper part of the tube empty. When the external temperature rises the mercury expands and once more ascends. Early in the eighteenth century the thermometer was made of practical use by fixing a scale alongside it, divided into steps or grades. If we select the freezing-point of water and call it zero, and indicate the boiling-point of water as 100, we may divide the intervening space into 100 grades, and so obtain a "centigrade" thermometer, introduced by the Swedish astronomer, Celsius, in 1742. Previously, in 1721, the German physicist, Fahrenheit, adopted another scale where the lowest temperature that had been noted at that time was taken as zero, and the freezing-point of water as 32°, while 180° above that, or 212°, was the temperature of boiling water. Placing the two scales side by side (Fig. 21) the values of the degrees in each may be readily compared. There is no doubt that the centigrade scale is by far the more convenient, and it is that scale that is almost always used in scientific work, but the Fahrenheit scale is usually the one found on thermometers sold in this country, unless the centigrade be specially asked for.

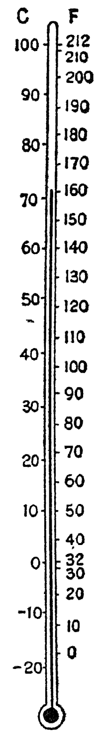

FIG. 21.—THERMOMETER.

The Air Pump—GUERICKE.—Torricelli, in making his barometer, obtained a space at the top of the tube that contained nothing; such a space is called a vacuum. The question then arose, Could a vacuum be obtained without using mercury? A method of achieving this was devised by Otto Guericke, burgomaster or mayor of Magdeburg in Prussia. The principle of his contrivance may be understood from Fig. 22. A is a jar in which it is desired to produce the vacuum. B is a cylinder firmly attached to A, but opening into it by a close-

fitting valve, D. C is a piston also provided with a valve, E, opening upwards. If the piston be pressed down to the bottom of the cylinder the valve D closes and E opens to allow the air in B to escape. If the piston be then pulled up the valve E closes, owing to the pressure of the outside air upon it, and the valve D opens owing to the efforts of the air in A to escape into B. The amount of air originally in A will now fill both A and B, and will naturally be rarefied. If the piston be again pressed home, the rarefied air in B will escape through E and the valve D will close. If this performance be repeated again and again the air in A will become more and more rarefied, until at last the air pressure in A becomes insufficient to raise the valve D. The machine is by no means perfect, for in addition to the fact that there is still some air left in A, there is the danger of leakage at the joints and valves.

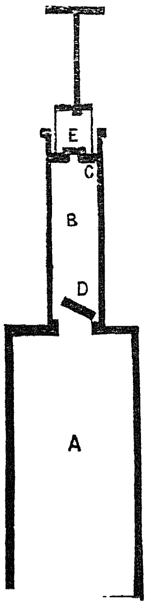

FIG. 22.—GUERICKE'S AIR-PUMP.

Atmospheric Pressure.—In order to show his discoveries on air pressure Guericke arranged a demonstration before the Emperor and his court. He obtained two large metal hemispheres whose rims were ground to fit each other perfectly (Fig. 23). One of these had a nozzle and tap which could be attached to an air-pump. When the rims were well greased and fitted together, he, as far as possible, exhausted the air in the sphere and showed that enormous force was required to pull the hemispheres apart. It is easy to estimate how great this force may be, supposing that the sphere contains no air at all. If the external surface of the sphere be equal to one square yard, or 1,296 square inches, and since the pressure of the atmosphere is 15 pounds on the square inch, it is obvious that it would take a force equivalent to more than 8½ tons to pull the hemispheres apart.

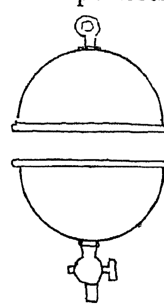
FIG. 23.—THE MAGDEBURG SPHERES.

Attraction and Repulsion in Electrified Bodies.—Guericke had heard of Gilbert's experiments with amber, sealing-wax and other substances, and proceeded to devise new experiments of his own. He found that if he suspended a pith ball at the end of a silk thread and brought near to it a stick of sealing-wax that had been well rubbed, the ball was at once attracted to the wax and adhered to it. Having absorbed electricity from the wax it was then repelled, and would not again approach the wax until it had lost its charge. Guericke rightly concluded that an electrified body attracts a non-electrified one, but repels one which is similarly electrified. He was also the first to notice the spark and the crackling sound when electricity jumps across the gap between two electrified bodies —in short, lightning and thunder on a miniature scale. How important all these simple observations were will be understood when we come to speak of Faraday, who worked on the same subject a century and a half afterwards.

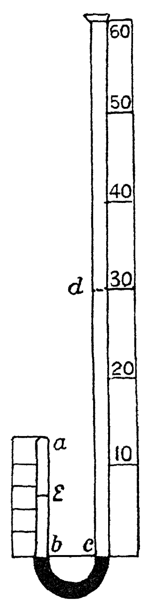

FIG. 24.—BOYLE'S LAW.

Law of Compressibility of Gases—BOYLE.—There was one distinguished man who lived about this time who, though he was renowned for his work on chemistry, made his mark also in physics. This was Robert Boyle. After his schooldays were over, he travelled on the Continent for five years for the sake of his health, for he had always been a sickly youth. He returned to England in 1644, and, as he was born in 1627, he was only a lad of seventeen when he began serious work on science. He had heard of Guericke's air-pump, and, in conjunction with his friend Robert Hooke, made a new and better one, and with its aid began to experiment on gases generally. He made one very notable discovery with regard to them which is always known as "Boyle's law." He took a bent glass tube (Fig. 24), closed at the shorter end, and poured into it some mercury, shaking it carefully until it stood at the same level in both legs of the

tube. The gas in *a b* was, of course, at normal air pressure. He next added mercury to the long leg of the tube up to 30 inches, *c d*, representing the pressure of two atmospheres, and found that the gas in *a b* had contracted to *a e*—*i.e.*, to one-half its original volume. Again he added 30 inches of mercury, and found that the gas was now compressed to one-third. Boyle's law of the compressibility of gases is, therefore, that, provided the temperature be constant, the volume of a gas varies inversely with the pressure to which it is exposed.

The Nature of Light—NEWTON.—It was in 1669 that Newton became professor of mathematics in the university of Cambridge, when he was only twenty-seven years old. His duties were to lecture once a week on some subject connected with mathematics, physics, or astronomy—a wide range of choice and quite untrammelled by that bugbear of the modern teacher, an examination syllabus. Newton selected optics, and very soon his lectures became a description of the discoveries he himself was making in that subject. From his notebooks we have learnt that he was busily engaged in trying to make better lenses than he could purchase in the shops, and yet his own productions did not satisfy him, for the images were blurred and indistinct. At last it struck him that the fault might lie not in the lenses but in the light itself.

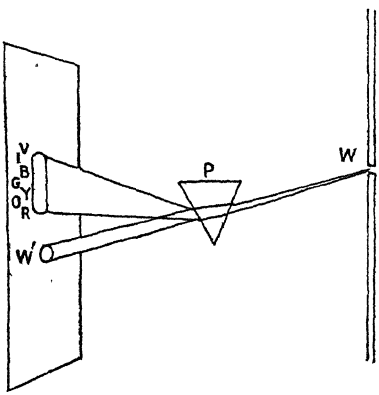

FIG. 25.—DISPERSAL OF LIGHT BY A PRISM.

If a small hole be bored in a window shutter (Fig. 25, W), so that light can enter only by that pathway, and if a white sheet be hung on the opposite wall, the beam will make a circular spot of white light on the sheet. Now obtain a three-sided glass prism, P, and introduce it in the path of the ray. It will be found that the prism has changed the direction of the beam and has spread it out into a narrow ellipse, V R,

coloured violet at the top and red at the bottom, with indigo, blue, green, yellow and orange in between. Although this effect of a prism had long been known, Newton was puzzled to account for the band of colour being in the form a of very flat ellipse. To answer the question place a screen (Fig. 26, S) between the prism, P, and the wall and adjust it so as to allow only one of the seven colours—say, green—to pass through a hole, H, in the screen. This beam will form a circular green disc on the wall, and if a second prism, P, be inserted between the screen and the wall, the green ray will be bent out of its path, but will not be spread out into any other colours. Since the colours merge into each other, it is obvious that the terminal ones will have rounded ends, and that the whole will form a long narrow ellipse. Thus Newton discovered that white

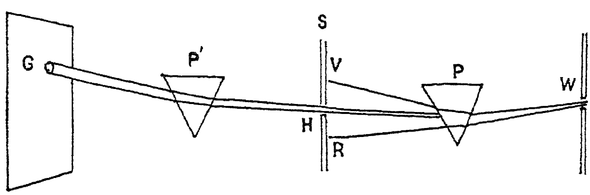

FIG. 26.—ANALYSIS OF THE SPECTRUM

light is made up of seven chief coloured rays, which being differently bent (refracted) are thus separated by a prism.

One startling conclusion follows from this experiment. If white light be passed through a sheet of red glass, the glass does not colour the white light red, as most people suppose; it merely blocks off all rays except red. If white light falls on a grass field we say the grass is green, but that obscures the truth. The grass only appears to be so since it absorbs all other rays save green and transmits that ray to our eyes, creating the sensation in our brains that we call green. If we chop up a leaf and soak the fragments in alcohol, we obtain a brilliant green solution, and if we hold this solution, contained in a glass vessel with parallel sides, between our eye and the source of white light, we have practically a green window-pane that has absorbed all rays save green.

The belt of colour obtained by splitting up white light by

means of a prism is termed a "spectrum," and the instrument, known as a "spectroscope," has proved of very great service in analysing the light of various substances, both on our own earth and also in the sun and stars.

Chromatic Aberration.—These enquiries were all made with the view of finding out why the light that passed through a lens made an indistinct image. Since all the coloured rays are differently bent, or refracted, when they pass through a lens, it follows that they must have different foci, and the defects in the lenses that Newton bought or made become at once explicable.

A beam of white light, W W′, strikes a lens, L L (Fig. 27). [In order to simplify the figure only the outermost rays are represented.] As the red rays are least refracted they will come

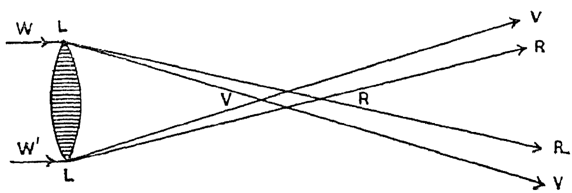

FIG. 27.—CAUSE OF CHROMATIC ABERRATION.

to a focus, R, farther away from the focus of the violet rays which are refracted most, V, the other rays coming to foci between R and V. Now if a white card be placed anywhere between V and R, or beyond these points on either side, a coloured blur is obtained. This is termed "chromatic aberration" or "colour wandering," and Newton decided that, since the fault lay in the properties of light and could not be remedied, it was useless to continue making lenses. He therefore devoted himself to making telescopes in another way. He was, however, too hasty in concluding that chromatic aberration was incurable, for, two years after his death, it was discovered that two kinds of glass, known as "flint" and "crown" glass, dispersed light rays differently, and that if these varieties of glass were properly combined, one remedied the defects of the other. Such lenses are called "achromatic"—*i.e.*, not giving colour haloes.

The Reflecting Telescope.—If a beam of light strikes a concave mirror, the rays are reflected and converge to a focus, but there can be no chromatic aberration in this case, for the rays do not pass through any glass and are thus not refracted before reaching the eyepiece. Newton's telescope (Fig. 28) was constructed on this principle.

A is a concave mirror, made of a mixture of copper and tin, placed at the end of a tube. A beam of light, B B′, strikes the mirror, is reflected from it, and focussed at C; but, before reaching C, it is caught by a plane mirror D, set at an angle of 45°, and reflected to the eyepiece, E, fixed in the side of the tube, where the image is viewed by the eye. This is called a "reflecting telescope," and it was improved many years after Newton's day by another great astronomer, Sir William Herschel, and is the type of instrument in use in most of the great observatories of the world at the present day, although, of course, much more elaborate in detail.

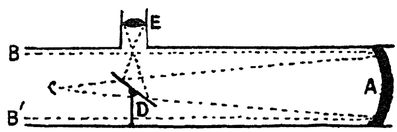

FIG. 28.—NEWTON'S TELESCOPE.

A Theory of Sound.—After having solved these problems in optics, Newton turned his attention to the question of sound. It had been known since the days of Pythagoras that sound was due to the beating of puffs of air on the drum of the ear, but the

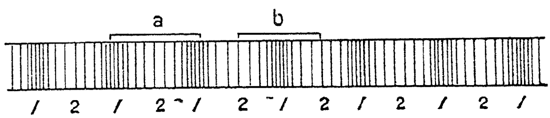

FIG. 29.—SOUND WAVES IN AIR.

question that remained unanswered was how the beat was carried from its source to the ear. When a pistol is fired the air particles in front of the muzzle are forced closely together and pass on the bump, so to speak, to those farther away, but being elastic they rebound, and hence there is a constant succession of bumps and rebounds in the air particles between the pistol and the ear. When the air particles are packed closely together (Fig. 29, 1, 1, 1), it is called a "condensation," and

when they are separate from each other, a "rarefaction" (2, 2, 2). The distance between any two condensations (*a*) or any two rarefications (*b*) is termed a "sound wave." If the waves be long and oscillate slowly the "pitch" of the note is low; if short and rapidly, it is high.

That it is really the air that carries the sound may be easily proved by placing an electric bell under the exhausted receiver of an air-pump and setting the bell ringing. The hammer will be seen beating, but no sound will be heard until the tap of the receiver is opened and air is allowed to enter, when the bell will be heard at once.

Newton also calculated the speed of sound, and found that it travelled at the rate of about 1,100 feet per second, or a mile in five seconds. So that if one hears a thunder-clap twenty seconds after seeing the flash, one may judge the flash to have been about four miles off.

The Nature of Light—the Corpuscular and Undulatory Theories.—In addition to explaining how light behaves when it passes through a prism, Newton also tried to find out what light itself is. He thought it was due to infinitely minute particles constantly streaming off from luminous bodies, and that the impinging of these particles on our eyes gave us the sensation we call light. This was known as the "corpuscular theory," but another theory, put forward by the Dutch astronomer Huygens, soon became a rival to it. Huygens's view was that light came to our eyes in waves just as sound came to our ears. But he knew that the air ends a comparatively short distance above the earth's surface, so that he had to invent something that would carry the waves from the most distant star to our earth, a something thin and elastic, filling the whole of space. Newton had previously postulated such a hypothetical medium, to which he gave the name of "ether" (æther). It was, Huygens said, the undulations of ether that gave us the sensation of light, and hence Huygens's explanation is known as the "Undulatory Theory."

The Speed of Light.—Newton made no attempt at estimating the rate at which light travels. Every one thought that light was instantaneous, and they were fully justified

in so thinking. The only one who appears to have had some doubts on the subject was that astute old philosopher, Galileo.

About 1670, Olaus Roemer, a Danish astronomer, was on one occasion studying the revolutions of Jupiter's satellites, and noticed that they did not always pass into Jupiter's shadow at the times predicted in the astronomical tables. It occurred to him that if light reflected from these satellites took a certain time to reach our eyes, these times should differ according to whether the satellites were viewed from the earth when it was in the part of its orbit nearest to Jupiter (Fig. 30, E), or in the part farthest away from it (E′). He worked out the

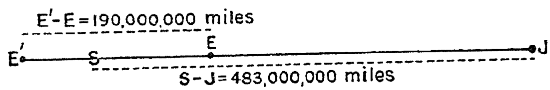

FIG. 30.—VELOCITY OF LIGHT.
EE′, Earth; S, Sun; J, Jupiter.

difference between the predicted and the actual time of a satellite's eclipse, and found it to be sixteen minutes thirty-six seconds, or roughly 1,000 seconds. Now the distance across the earth's orbit is about 190 millions of miles, and as light took 1,000 seconds to travel that distance, its speed was obviously 190,000 miles per second, a figure very close to that arrived at by the latest workers on the subject. In 1926 an estimate was given by the American astronomer and physicist, Michelson, which made the velocity to be 187,372 miles per second. No wonder most people believe that light is instantaneous, taking as it does only about eight and a half minutes to travel from the sun to our earth! This enormous velocity of light is a number that ought to be remembered, for we shall meet with it again when we consider the advances in science that have taken place in our own time.

§ iv. CHEMISTRY

We need not spend much time over what passed for chemistry in the seventeenth century. It is only some 300 years since people believed that there were only four elements

as Aristotle had taught—viz., earth, air, water and fire. Now, of course, earth is recognised as a very complex mixture of compounds of all sorts of elements; water is a compound of two elements; air is mainly a mixture of two elements, and fire is not a substance at all. The alchemists held there were only three elements: sulphur, mercury and salt.

In spite of such crude ideas, a good deal of research of a kind had been carried out; for the Greeks left behind them recipes of how to extract metals from their ores and how to make alloys of two or more metals. Geber discovered some of the strong acids, and showed how to distil liquids and to sublimate solids; but a science of chemistry must be an organised body of facts, not merely a collection of pieces of information on unrelated subjects, however interesting and important in themselves.

The Definition of an Element.—Robert Boyle, the discoverer of the law of the compressibility of gases, has often been called the "Father of chemistry," and his chief claim to that title rests on the book called "The Skeptical Chymist," in which he ridiculed the old ideas about elements. He defined an element as something that cannot be broken down into two things different from itself; it is impossible to split gold into anything but gold, or silver into anything but silver, and so on. But, although his definition of an element is correct, his facts were often wrong, for he thought that lime, potash and magnesia were elements because he could not decompose them.

The Phlogiston Theory.—A curious theory of combustion was started about the end of the seventeenth century by two German chemists, Becher and Stahl. It was based on an entirely erroneous idea, but it was firmly believed in at the time, and retarded the advance of chemistry for nearly a century. This was called the "phlogiston theory," from a Greek word meaning "something inflammable." It was held that every substance that was combustible was composed of a "calx," or ash, and a certain amount of a substance called "phlogiston." Some bodies, it was thought, had much phlogiston and very little calx in their composition, and such bodies—*e.g.*, charcoal—burnt readily, while others, such as lime, had an excess of

calx and very little phlogiston. When a combustible body was burnt it lost its phlogiston to the air and could get it back again only from the air, or from some other body that had a surplus of it.

The Nature of Air.—Boyle had made some interesting experiments, partly chemical, partly biological, which led to some very important results later on. He showed that a lighted candle went out when it was placed under a bell-jar from which the air had been extracted, and that small animals died when similarly treated (*cf.* p. 21). Hence he concluded that air was essential to combustion and to life. He gave an account of his experiments at Oxford, where one of his audience was a young doctor, called Mayow. Mayow was born in Cornwall in 1645, and, after taking his degree, began to practise at Bath. He died when he was only thirty-three, so that he must have been a mere youth when he heard Boyle lecture.

From what he learned he concluded that there must be something in the air that supported flame and life, and that this something could be only a relatively small part of the air, since a candle went out long before all the air in the bell-jar was exhausted.

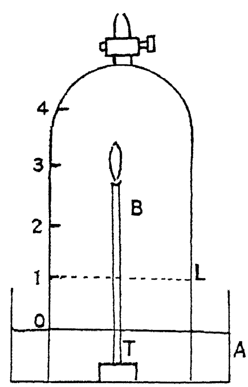

FIG. 31.—MAYOW'S EXPERIMENT.

Obtain a large bell-jar (Fig. 31, B) with a tap at the top, and divide its contents into six equal parts, and also a sufficiently large basin, A. Fix a lighted taper in a lump of plasticine at the bottom of the basin, T, containing water, and quickly cover it with the jar until it stands opposite the zero mark, the tap meanwhile remaining open; then close the tap. At first the water will sink below zero, because the taper has heated the air and caused it to expand, thus forcing the water down. Presently it will rise, and go on rising so long as the taper continues to burn. When the taper goes out, and when the bell-jar and its contents have stood, it will be found that the

water will have risen to a higher level nearer the dotted line L, showing that something of the air originally in the jar has disappeared.

Exactly the same kind of thing happens if a mouse, or other small animal, be placed in the jar in lieu of the taper; the water rises and the animal dies. Mayow, from his experiments, decided that there were two gases in the air, one of which, amounting to about one-fifth of the whole, supported combustion and life; the other did neither, but was neutral, or inert. The first he called "spiritus nitro-æreus," or "fire air," but to the other he gave no name. We know the first nowadays as oxygen and the latter as nitrogen. It is often stated in textbooks of chemistry that a chemist, called Priestley, discovered oxygen, exactly a century later, but the honour might be given to Mayow, although Priestley rediscovered it and was the first to isolate it.

Chemistry was thus in a very backward state in the sixteenth and seventeenth centuries, and for two reasons—first, because the facts that had been discovered were relatively few in number; and, second, because what was known was not organised, and it is only organised knowledge that constitutes a science.

§ v. Biology

The sixteenth and seventeenth centuries were rich in great names connected with the science of biology—the science of life. There were botanists who recommenced the study of plants where Theophrastus left off, 2,000 years before; there were zoologists who carried on the story of the animal world as begun by Aristotle, and there were men who eagerly explored the structure of the human body and proved themselves worthy successors of Hippocrates.

Nowadays, when we speak of a man as a botanist or a zoologist, we mean one who endeavours to study a plant or an animal from every point of view, as a structure made up of definite parts, as a living machine, feeding itself, adapting

itself to its surroundings and multiplying itself, or producing progeny like itself. The biologist also studies how plants are related to other plants, and animals to other animals, where they are to be found, and how they came into existence. The biologists of the sixteenth century attempted something in the way of describing the structure of the organisms they studied, and tried to classify them in groups, but they knew little or nothing of how they lived or how the machines worked.

The Herbalists.—The first botanists were what we call "herbalists"—*i.e.*, men who described the structure of plants growing round them, chiefly that they might be the more easily recognised as sources of food or drugs. Among these the more notable were Brunfels, Fuchs, Bock and Cordus, all of whom lived before the close of the sixteenth century. The chief among the earlier zoologists was Gesner, who wrote an elaborate work on natural history, giving an account of all the animals then known.

The Pioneers in Modern Medicine.—In medicine one great name had come down through the centuries, that of Galen, a physician of Asia Minor, where he was born in the early part of the second century, and who, after studying at Alexandria, became the medical attendant on the Emperor Commodus at Rome. His books were regarded as the last word on every thing concerned with health and disease, and to question them was heretical in the highest degree. But there was one man who lived in the beginning of the sixteenth century who dared to criticise Galen, a learned chemist, as chemistry was understood in those days, a man who set himself the task of exposing all the humbug and fraud that passed for medicine, and who fought for common sense in the treatment of disease. This man was Paracelsus. Like all other great reformers he got himself into trouble, not this time with the Church, as Galileo did, but with the universities and the medical profession. He fought against authority as represented by Galen, and preached the sound doctrine that Nature herself was the great healer, and that the physician's business was to provide her with what she required to fit her for the battle she was waging against disease.

The First Anatomist—VESALIUS.—But Galen's teaching was attacked by others, who vigorously criticised his ideas about the structure of the human body. The chief of these was Vesalius, professor in Padua, where he taught anatomy by dissecting the body before his students, and insisting that if the actual dissection contradicted what Galen had said, then Galen must be ignored.

The Circulation of the Blood—HARVEY.—The fame of Padua as a school of anatomy and medicine tempted to it students from all over the world, even from far-away England, and one of these was William Harvey, whose name will be famous for all time as the discoverer of the circulation of the blood. He was the son of a Kentish farmer, and was born in 1578. About twenty years later, after studying at Cambridge, he went to Padua, where he worked under Vesalius's successor, Fabricius, who discovered the valves in veins. When Harvey returned to England he took his doctor's degree at Cambridge and settled down to practise medicine in London, but at the same time gave lectures on the structure of the body and how the various organs worked together for the good of the whole. It was during this time that he prepared his great work, "On the Movements of the Heart and Blood," a book quite as famous in its way as Copernicus's "Revolutions of the Celestial Bodies." In order to appreciate fully Harvey's epoch-making discoveries, it is essential to know what people believed on the subject before his time.

Aristotle thought that blood was made from food in the liver, that it flowed from the liver to the heart, and went from there to all parts of the body by way of the veins. The arteries were the means by which a "spirit," or "very subtle essence," was distributed through the body, although Galen thought they might contain blood also. This was doubtless because the arteries in a dead body were found to be empty. The pumping that caused the movements of the blood was believed to be the act of breathing. The heart was divided into two chambers, right and left, which communicated with each other through a porous partition, and there were two kinds of blood, one that flowed from the liver to the right side of the heart,

from which it went to the lungs and other organs by the veins, and another kind which followed the same course by the arteries. It was known that the heart expanded and contracted, but it was thought that the expansion was due to a "spiritus" or gas inside it. The whole question was thus in a most confused state, and the so-called explanations were entirely misleading.

Now we come to Harvey's discoveries. To begin with, he recognised that there were two kinds of bloodvessels, arteries and veins, and that, in the living body, they both contained blood. He found that, if he tied an artery, it began to swell and throb on the side next the heart, and hence it was obvious that the blood flowed from the heart to the limb whose artery he had bandaged. When he tied a vein, say, in the arm, the part beyond the ligature—*i.e.*, on the side farthest from the heart—began to swell, but there was no throbbing. That meant that the blood was flowing from the limb to the heart by the vein, but was not actually being rhythmically pumped there. The purpose of the valves that Fabricius had found in the veins was now obvious; they did not prevent blood flowing to the heart (in the direction of the arrow in Fig. 32, A), but they did prevent it from flowing back from the heart (B); and, further, each throb or beat in the artery followed a contraction of the heart, not, as was commonly supposed, an expansion of it.

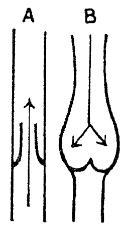

FIG. 32.—VALVES IN VEINS.

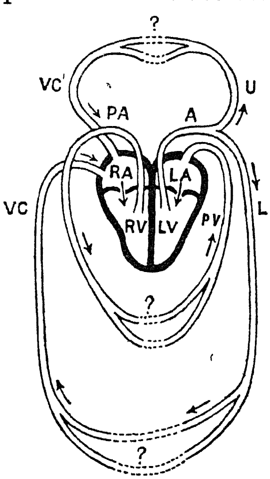

FIG. 33.—CIRCULATION OF THE BLOOD.

At length Harvey was able to give a full account of the whole matter (Fig. 33). To begin with, he said the heart has four chambers, the right and left auricles, RA and LA, and the right and left ventricles, RV and LV. The right auricle opens into the right ventricle, and the left auricle into the left ventricle, and both openings are guarded by valves so arranged that fluid may pass from the auricles to the ven-

tricles but not from the ventricles to the auricles. There is nothing in the way of a communication between the right and left sides of the heart at all, porous or otherwise. The ventricles have very thick muscular walls, and are therefore able, on contraction, to squeeze out their contents with considerable force.

From the left ventricle arises a large artery known as the aorta, A, which presently divides into two branches, the smaller branch passing upwards to break into many still smaller vessels (not shown on the figure) which supply the head and neck, the larger one similarly dividing into secondary branches to supply the trunk and lower limbs. Harvey failed to discover what became of the blood when it had reached the finest visible ends of the arteries. That was not made out until some years had elapsed.

Harvey next saw that the blood from the head and neck and from the rest of the body was carried back to the heart by two large veins (VC, VC′) and poured into the right auricle, from which it passed to the right ventricle. Harvey noticed that the blood which left the heart by the aorta was bright scarlet, but that what came back by the veins to the right auricle was dull crimson. From the right ventricle the blood was then pumped by a large artery called the pulmonary artery (PA) (Lat. *pulmo*=lung) to the lungs, where, apparently, it regained its bright scarlet colour, and was carried back from the lungs by a pulmonary vein (PV) to the left auricle, from which it passed into the left ventricle and from which it started once more on its long journey.

It will be noticed that Harvey left two important questions unsolved, the first an anatomical one—What came in between the extreme ends of the arteries and of the veins in the body and in the lungs? and, second, a physiological one—What was the meaning of the change in the colour of the blood after it had passed through the body and after it had passed through the lungs? The first question could not be answered until a new instrument, the microscope, had been invented, and the second awaited the determination of the relation of the living organism to air, and especially to that part of it which Mayow found was essential to life.

The Microscope.—To a Dutch optician, named Jansen, belongs the credit of having discovered the principle of the compound microscope. In its simplest form (Fig. 34) it consists of a lens, L, nearest the object to be examined, which makes a picture, F, inside the tube of the microscope, and a second lens, E, next the eye, which magnifies the image. Our modern microscopes are often very complex instruments, for both the object glass and the eyepiece are composed of several lenses, and, in order to see through an object, there is fixed to the stand a platform or stage, P, on which the object is placed. A hole in the stage permits light to be reflected from a mirror, M, swinging below the stage, so as to reach the eye through the various lenses in the tube. There are also screws by which the tube may be adjusted to suit the magnifying power of the lenses and the eye of the observer. The compound microscope has now become one of the most valuable instruments the biologist possesses, and is to him what the telescope is to the astronomer.

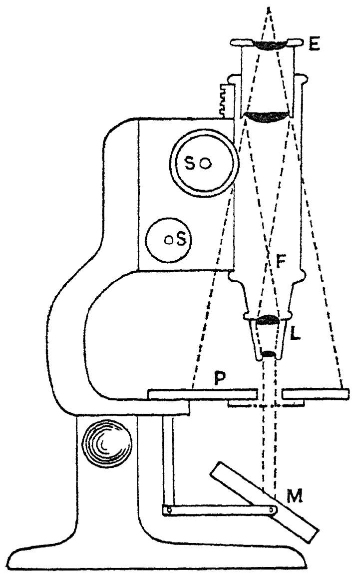

FIG. 34.—COMPOUND MICROSCOPE.

The Royal Society.—At this point we must take note of one event that took place about the middle of the seventeenth century that affected not only biology but all the sciences. This was the foundation of what was called the "Invisible College," a sort of club or society composed of those who were interested in science and in the various questions that were being discussed by the learned men of the day. The headquarters of the society was at a house in the centre of London, called Gresham College, after a famous London merchant, Sir Thomas Gresham, who bequeathed it and money for its support

to the Mercers' Company, on condition that courses of instruction should be given there on certain scientific subjects. This little band of workers included some of the most famous men of the century, such as Boyle, Mayow, Huygens, Halley, Newton and many others. After the Restoration, the King was induced to take an interest in their work, and at length he officially recognised it by giving it a Charter, after which, in 1662, it became the most important centre for the discussion of scientific questions in Great Britain, if not indeed in the world, under the title of the Royal Society.

The Discovery of the Cell—HOOKE.—Robert Hooke, who had been assistant to Boyle when he was working at the compressibility of gases, was professor of geometry at Gresham College, and also had charge of the setting up of experiments for the Royal Society. He was keenly interested in the microscope, and made one of his own which he used constantly. He cut thin slices of all sorts of bodies, both vegetable and animal, and, with the aid of his microscope, discovered that they were "all perforated and porous, much like a honey comb," and to these pores he gave the name "cells." He published his observations in 1665 in a book which he entitled "Micrographia," or "little pictures."

Capillaries and Blood Corpuscles—MALPIGHI.—Meanwhile, in Italy, there lived a very distinguished biologist called Malpighi, who was professor first at Pisa and then at Bologna. He also had the assistance of the microscope, and was able to solve the problem of the connection between the visible ends of the arteries and veins, by showing that they were united by an exceedingly delicate network of very fine tubules called "capillaries." These he saw perfectly clearly in the transparent lung of the frog. He also showed that the blood was composed of a colourless fluid in which floated myriads of rounded red discs, the "blood corpuscles" (Fig. 35). Each corpuscle is a biconcave disc, *b*, about $\frac{1}{3200}$ of an inch in diameter, pale reddish-yellow in colour, but scarlet to crimson when seen in mass. Among them

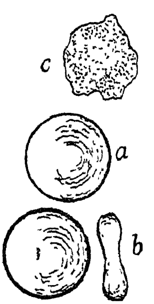

FIG. 35.—BLOOD CORPUSCLES.

may be seen "white blood corpuscles," *c*, discovered long after Malpighi's time, but these are relatively few in number, two or three for every hundred of the red ones.

Malpighi also made many other important discoveries in the structure of the human body, such as the different layers of the skin and the constituent parts of the kidney, in both of which certain regions are still known by his name. He also studied the lower animals, and wrote a full account of the life-history of the silk-worm, which was published by the Royal Society, of which he was a foreign member. Finally, he examined the structure of plants, and wrote a long paper, or rather book, on the subject, which was also published by the Royal Society. In this latter domain he was, however, anticipated by another biologist, this time an Englishman, Nehemiah Grew.

The Anatomy of Plants—GREW.—Nehemiah Grew, who was born in 1641, was a physician, first in Coventry and later in London, but he appears to have spent most of his time in studying the anatomy of plants. The book in which he published his researches was called "The Anatomy of Plants begun," and was profusely illustrated. Both he and Malpighi made attempts at explaining the functions of the structures they described, and sometimes they were fairly right, but in other cases entirely wrong. For instance, both of them held that sap was pumped through the vessels of the wood by a sort of rhythmical pulsation or "peristalsis," as it was called. No doubt they hoped to find something in the plant that would correspond to the circulation of the blood in the animal, but seeing that there was no heart in the plant, they invented the rhythmical squeezing of the wood vessels to take its place. Not long afterwards another biologist, Stephen Hales, showed that no such squeezing took place, and that there was no circulation in the plant comparable with that demonstrated by Harvey in the animal.

The Discovery of Stomata and Chlorophyll.—Both Malpighi and Grew recognised the presence of minute pores especially on leaves, the stomata (Fig. 36), which they correctly thought were intended to allow of the escape of superfluous water in

the form of vapour, or to admit air. Grew paid some attention also to the green pigment in plants which we know as "chlorophyll," and was the first to extract it from leaves by the aid of olive oil. What it was for he had, of course, not the vaguest idea. He also noted how certain plant organs, such as tendrils, twined round supports, and how the leaves of other plants closed together at night, but the explanation he gives is a purely mechanical one and very far from the truth. Both Grew and Malpighi watched the germination of seeds and traced the stages through which they went, but the earliest features in the development of the embryo could not be made out with the apparatus they possessed.

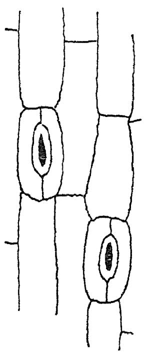

FIG. 36.—STOMATA.

Biogenesis and Abiogenesis—LEEUWENHOEK.—In Holland, the birthplace of the microscope, there was born in 1623 a man called Anthony van Leeuwenhoek, who took a keen interest in the microscope. He was well off, and thus could afford to spend time and money on his hobby. He both made and collected microscopes; indeed, it is said that he possessed no fewer than 274 of them! But he made use of them also, and to some purpose. He traced the capillaries in the tail of the tadpole and in the web of the frog's foot, and his description of them is even better than that given by Malpighi. His most important discovery, however, was of the minute animals we now call "Protozoa," but which he called "animalculæ," and of bacteria or microbes, which he found in stagnant water. His drawings are so accurate that modern biologists can actually name the organisms he figured.

It had long been held that various kinds of living things could arise from dead matter, and all sorts of ridiculous stories were accepted as true—such, for example, as the account given by the Belgian chemist, Van Helmont, of how he obtained mice from cheese wrapped up in soiled linen.

It was generally supposed that maggots might arise spontaneously from putrefying meat, until, in 1668, Redi, an Italian doctor, showed conclusively that the maggots arose from eggs

that had been laid in the meat by flies. Now, however, that Leeuwenhoek had discovered these exceedingly minute creatures, the animalculæ and bacteria, the suspicion arose afresh that they might have sprung from dead material. The theory that every living thing springs from another precedent living thing of the same kind is now called "biogenesis" or "life origin," and the contrary view, that living things may arise from non-living matter, is called "abiogenesis" or "non-life origin." After careful experiment, Leeuwenhoek decided in favour of biogenesis, and in this view he is supported by all recent authorities on the subject.

That Leeuwenhoek was correct in his conclusion may be proved in the following way. Prepare some beef extract and pour some of it into two test-tubes (Fig. 37), and plug one of them, A, with cotton wadding. Heat both of them in a pan of boiling water for at least half an hour, and leave them to cool. In the course of a few days the fluid in B will have become turbid, and will give off an unpleasant odour, but that in A will remain clear. With the aid of a powerful microscope the turbid fluid will be found to be swarming with exceedingly minute organisms, while the fluid in A will contain none. How is this explained? Bacteria are the smallest living organisms known and occur freely, and especially in air. Most of them are killed by prolonged boiling, but the boiling must be thorough. Some bacteria cause putrefaction in such food materials as beef-tea, but when the test-tubes are boiled all the bacteria already there are killed. When the tubes cool more bacteria from the air fall into B, but they cannot enter A because of the plug of cotton which has been sterilised by the passage of steam through it during boiling. Hence the fluid in A remains good, while that in B goes bad. If the bacteria were really derived from the (dead) meat extract, there is no reason why they should not have appeared equally in both tubes.

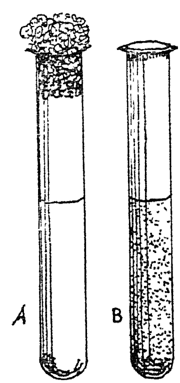

FIG. 37.—BIOGENESIS.

There are two more names that we associate with progress in the science of biology in the seventeenth century, both of them clergymen, but with very different outlooks on life, and very different tastes in research. The one was the Rev. Stephen Hales and the other the Rev. John Ray.

The Foundations of Plant Physiology—HALES.—Stephen Hales was a student of divinity at Cambridge at the end of the seventeenth century, when Newton was professor there, and perhaps he came under the influence of that great man; at all events, he became thoroughly saturated with thescientific spirit, and learnt as much about physics and chemistry as he did about theology. In 1708 Hales was appointed to a curacy at Teddington on the Thames, where he remained for the rest of his life, and where all his scientific work was done. His results appeared in a volume called "Statical Essays," part of it in 1727, the year Newton died, and a second part six years afterwards.

It will be remembered that Grew believed in a circulation of sap in plants, something like that of the blood in animals, and fancied he saw the sap being pumped up the vessels of the wood by a sort of rhythmical squeezing. Hales, by very ingenious experiments, convinced himself that the sap did not circulate, but only ascended, and that there was no pulsation in the wood vessels, although there was a pressure that varied from time to time according to changes in temperature, light and darkness, seasons of the year and other conditions. This continuous but varying stream ascended from the roots to the leaves where the surplus water was exhaled as vapour through the stomata (Fig. 36). He measured the pressure exerted by the ascending sap and the rate at which it flowed. What caused it to rise? He was not so confident in answering this question, but he thought that the water was forced upwards by what he called "root pressure" or *vis a tergo* (a force from behind), carried onwards by capillarity, or the tendency liquids have to rise in very narrow tubes, and finally by the pull of evaporation at the leaves, the *vis a fronte*, or tug from the front, so that more water must ascend to replace what had been given off.

Hales made his experiments on sap pressure by means of

a simple instrument called a "manometer" (Fig. 38), which consisted of a twice bent U-tube, one leg of which was firmly attached to the stem of the plant, while the other bend of the U contained mercury. At first the mercury will be at the same level in both legs, but as the sap exudes from the stem it will press the mercury down in the nearer leg and cause it to rise in the other, and any variations in the heights of the mercury will indicate corresponding variations in the pressure of the sap. Hales attached these manometers to several branches of the same tree, and so was able to observe the variations of the pressure in different parts under different conditions.

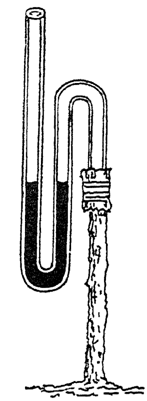

Fig. 38.—Manometer.

Another point that Hales made out was the pathway by which the sap ascended. If a branch of a tree be cut across, three prominent regions may be recognised—a pith in the centre, then a ring of wood, and outside that a ring of what is popularly called "bark." If a young branch, still attached to its parent stem, be selected and a ring of "bark" down to the wood be cut off it, preferably just below the bud, the leaves beyond the ring do not wither, showing that the sap is still ascending by the wood, while just above the ring the bark region begins to swell. This points to the fact that something is descending via the bark, for its further downward passage is stopped by the removal of that layer; the bud above the ring, being better nourished than usual, opens before its neighbours.

Hales's book, though written before the composition of air was accurately known, and while chemistry was still in its infancy, was a wonderful record of careful experiment; while the results he obtained, and the sound deductions he drew from them, entitle him to rank as one of the foremost biologists of the seventeenth century.

Classification of Animals and Plants—John Ray.—Ray was a biologist of a very different stamp. He was in no sense an experimenter like Hales, and took little or no

interest in the life of the plant or animal; he was, on the other hand, an enthusiastic collector and classifier. While at Cambridge he had as a pupil a young man called Willughby, who possessed what Ray had not, abundant private means. For several years the two men travelled over much of the Continent, collecting plants and animals, and they continued to work together on their return, until Willughby died in 1672. In his will he left Ray a pension and funds to complete the work they had begun together. As originally schemed out, Willughby was to have done the animals and Ray the plants, but in the end Ray did far more than his share, although he gives Willughby more than ample credit for what he had accomplished.

Classification has changed so completely from what it was in Ray's time that his attempts are only of historical interest. The first volume published treated of quadrupeds, or four-footed animals, which Ray divided into those that laid eggs from which the young animal arose—*e.g.*, a frog—and those whose young were born alive—*e.g.*, a cow. The first group was called "oviparous," the second "viviparous." The viviparous animals were next divided into groups according to the number of toes they possessed, and then after the number and nature of their teeth. Birds were either inhabitants of land or of water, and their subdivision rested on the nature of their beaks and claws, the length of their legs and the kind of food they ate. Fishes were classified very much as they are at present. Insects were grouped into those that went through changes of form during their lives—*i.e.*, caterpillar, chrysalis, butterfly or moth—and those that developed directly without these changes. Ray made no serious attempt at describing or grouping the host of lower animals, such as worms, sponges, jellyfish, and so on; indeed, very little was known about these forms until the beginning of the nineteenth century.

The best part of Ray's book was the volume on plants. He started by separating off all the lower plants—such as ferns, mosses, mushrooms, moulds and seaweeds—as "imperfect" plants, because they had no flowers, and by far the greater part of his book deals with "perfect" plants—*i.e.*, those with

flowers. The so-called "imperfect" plants are, of course, no less perfect than the others, but their real points of difference were not made out until well through the nineteenth century. No one bothered about them; the flowering plants were those that caught the eye and were of the greatest service to mankind, and therefore deserved the most attention.

Ray divided the "perfect" plants into those that showed two primary leaves in the seedling and those that showed only one. The first he called dicotyledons—*e.g.*, wallflower, bean, or rose—and the second, monocotyledons—*e.g.*, lily or grass. These names are still in use, but Ray's subdivisions of these two groups have long since been discarded. It is remarkable how an error may persist if only it has a great name behind it. Ray divided dicotyledons into those with "simple" flowers, like a buttercup or a rose, and those with "compound" flowers, like a daisy. As a matter of fact, a daisy is not a flower at all, but a closely packed group of flowers or inflorescence, and the real flower of the daisy is just as simple or as complex as that of a buttercup. It is smaller, it is true, but that is all. Even the first botanist, Theophrastus, who lived nearly 2,000 years before Ray, did not make that mistake, for he points out quite clearly that a "capitulum" or "little head" of a daisy or dandelion consists of many small flowers, all arising together at the top of a common axis.

PART IV.—SUMMER

ADVANCES IN SCIENCE IN THE EIGHTEENTH AND EARLY NINETEENTH CENTURIES

§ i. Astronomy

After realising the tremendous change in the outlook on science in general and in astronomy in particular that followed Newton's great discovery of universal gravitation, it is not astonishing that there were many who believed that little was left to be discovered, although Newton himself said that the immense ocean of truth still lay unexplored before him.

The Velocity of Light.—Roemer, towards the end of the seventeenth century, had shown that light took about sixteen and a half minutes to travel from Jupiter to the earth. He made his calculations after a study of the eclipses of Jupiter's satellites, so that it seemed important to obtain some accurate information about those attendants on the greatest planet of the solar system, when, for instance, they were predicted to pass into his shadow as seen from our earth, and when they actually did so. This question of the velocity of light, and the related one of the distance of the stars, greatly interested a young man called James Bradley, who was born a few years after Newton's "Principia" was published. Young Bradley was reared in what might be termed an astronomical atmosphere, for he spent much of his youth with an uncle who was himself a distinguished astronomer. Indeed, uncle and nephew made the first attempt at an accurate measurement of the distance of the sun from the earth, rather a difficult task when we think of the crudity of the instruments with which they worked.

In 1722 Bradley was elected professor of astronomy at Oxford, and he at once set to work on the transit of Mercury which was due to take place in the following year, and also on tracing the orbit of a comet that Halley had just discovered.

It should be remembered that these observations were made with a refracting telescope, which consisted of an object glass with a focus of over 200 feet placed at the end of a long pole. The measurement of the distance of the fixed stars was an even more difficult problem, and it may be as well to try and understand how this question is approached before looking at Bradley's efforts to solve it.

Stellar Parallax.—Sit in front of a window and fix on some object—say, a church steeple some distance away—and align it on a piece of paper gummed on the window-pane; then, keeping the body steady, bend the head slightly to the right; the paper spot appears to shift to the left (or to the right if the head be bent to the left). Push back the chair from the window as far as possible and repeat the observation. The spot will still appear to shift to the left or right with reference to the steeple, but the shift will not be so great. In short, the farther off the two objects are the less will be the apparent movement of the nearer one.

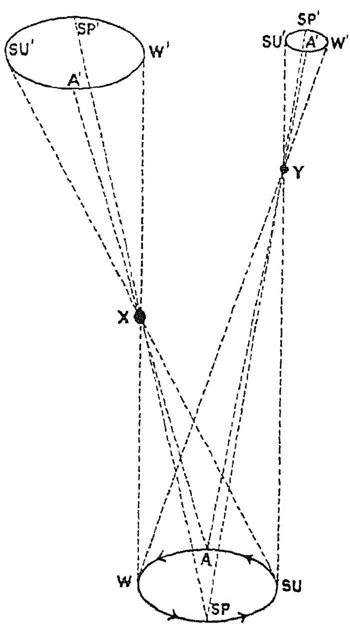

FIG. 39.—PARALLACTIC ELLIPSES.

Now the stars are at stupendous distances from us, but these distances vary. Suppose we select one star and watch it in relation to another star much farther off, and then move —say, from London to Edinburgh—about 400 miles. Will there be any apparent shift? If there be none, we may conclude that both stars are immensely far away. But 400 miles is a mere trifle when we are dealing with astronomical space, so for our purpose let us fix on two positions on opposite sides of the globe. Even then the two stars show no apparent shift. The only thing left is to take, as our base, opposite points

of the earth's orbit—*i.e.*, about 190,000,000 miles apart. The earth revolves round the sun in an ellipse, so that in mid-winter the earth might be at W (Fig. 39), and looking for our bright star we find it at X. If we continue the line W X, the end of it points to another far more distant star, W′. As the earth travels in its orbit, it reaches SP in springtime, and, again, looking at X, we find the line SP-X points to SP′ in the sky. Similarly when we are at SU in summer, SU-X points to SU′, and when at A in autumn A X points to A′. Thus the star X appears to describe a tiny ellipse in the sky corresponding to the ellipse the earth has described round the sun during the year. The astronomers call this a "parallactic ellipse," parallax meaning a slight alteration or deviation. Put more simply,

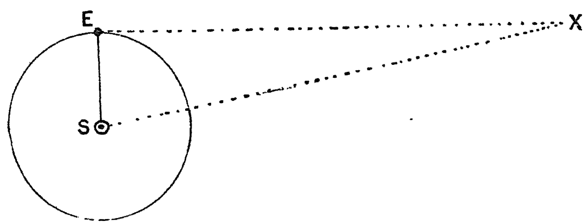

FIG. 40.—STELLAR PARALLAX.

if E (Fig. 40) be the earth revolving round the sun, S, and X be the star, then the angle made by the two lines drawn from X to either end of the radius of the earth's orbit, E S, is called the star's "parallax." Obviously the farther off X is the smaller will be the angle E X S, until, when X is at an infinite distance, the angle will be zero and the two lines E X and S X will be parallel. To measure angles so minute requires not only the very highest mathematical skill but also the very finest instruments.

If the star we are watching be farther away than X, say at Y (Fig. 39), we shall find it also describing an apparent ellipse in the sky, but a much smaller one, so we conclude that the nearer the star is to us the larger will be the parallactic ellipse, and the farther away it is the smaller that ellipse will be. How small these ellipses really are may be judged by the

fact that, if one be standing in the centre of a circle whose circumference is two miles distant, a penny placed on the circumference would cover the largest parallactic ellipse we know! No wonder that the problem baffled the very greatest observers until well into the nineteenth century, when astronomical instruments began to be sufficiently refined and accurate to enable such very delicate observations to be made. Yet this was the problem Bradley set out to solve.

Aberration of Light.—The first thing to do was to select a star, and Bradley chose one called "Beta Draconis," chiefly because it passed over the zenith at Oxford, and so enabled him to disregard any refraction of the stellar rays in their passage through the earth's atmosphere. He started his observations in December, 1725, and expected to see the star move to the north, but it did not! It moved to the south, and kept on doing so until March, 1726, when it was 20 seconds south of where it had been in December. In April it began to move north again, and in June reached the zenith, but it did not halt there; it went on northwards until it was almost as far north of the zenith as it had been south in the previous March. Then it turned south once more and regained its old place, just one year after it had begun its curious journey. Here was an entirely new kind of movement which was obviously not parallactic at all. Bradley at once gave up trying to determine the distances of the stars, and switched off on to this new problem. He began by watching the behaviour of other stars, and soon found that they all showed the same erratic movements to a greater or less degree.

In order to explain the phenomenon, he argued that since light takes a certain time to travel from a star to us, if the earth were at rest the ray would reach us in a straight line. But the earth is not at rest, it is moving in its orbit at the rate of eighteen miles per second, so that when a star is seen through a telescope we do not see where it *is*, but where it *was* sometime before. This is what is called the "aberration" or "wandering" of light, and this discovery at once brought Bradley into the forefront of the astronomers of his day.

Soon afterwards Bradley was created Astronomer Royal

in succession to Halley, and signalised his appointment by making another important discovery. He found that when the apparent movement of the star was complete it did not return precisely to the same spot it had occupied in the previous year. Since the days of Hipparchus, more than a century before our era, it had been known that the north pole of our earth describes a small circle in the heavens. Bradley's new discovery was that the circle was not a perfectly smooth curve, but a wavy one, each wave taking nineteen years to form. To this curious movement of the earth's pole was given the name of "nutation," or "nodding."

SIR WILLIAM HERSCHEL.—While Bradley was working at the problem of the aberration of light, there was born in Hanover a child who was destined, in time to come, to eclipse him entirely, although his rival spent his early days playing the oboe in a regimental band. This was William Herschel. He may have been a good musician, but he was not much of a soldier, for he deserted from the army after his first battle. Had he been caught he would probably have been shot, and the Hanoverian Guards would have lost an instrumentalist and science would have lost, perhaps, the greatest astronomer of all time. Anyhow, young Herschel escaped to England, and, after filling various musical posts, took up his abode in Bath, where he taught music on week-days to the inhabitants of that fashionable spa, and played the organ on Sundays in the Octagon Chapel.

It was during these early days—he was not yet thirty—that he devoted his leisure hours to the study of mathematics and astronomy, and brought over from Germany his brother, Alexander, who was an engineer by profession, and his sister Caroline, who proved of immense service to him in the years that followed.

Nothing less would satisfy him than to see with his own eyes the wonders of the heavens that others had seen and written about, so he set about making a telescope better than any he could afford to buy. After many attempts, in which he had his brother's help, he at last turned out an instrument that satisfied him, and with it began to carry out what

astronomers call "sweeping the heavens"—*i.e.*, exploring methodically every field of view the telescope presented.

Newton, it may be recalled, had given up the idea of a refracting telescope, and invented one where the light from the stars was reflected from a concave mirror, the rays being focussed half-way down the tube and transmitted by a flat mirror to an eyepiece set in the side of the tube (Fig. 28). Herschel greatly improved on this by tilting the concave reflector and so directing the rays sideways. They could thus be seen by the eye directly (Fig. 41).

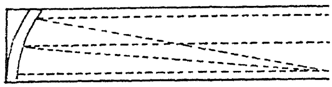

FIG. 41.—HERSCHEL'S TELESCOPE.

Discovery of Uranus.—One night, on March 13, 1781, to be precise, he was "sweeping the heavens" as usual, and noticed in one of the constellations, called "Gemini," or the "Twins," a new body that differed from all the other luminous points beside it in showing itself as a disc and not as a mere spark of light. He thought at first it must be a comet, but soon decided that it was not. The only other thing it could be was a new planet, a new member of the solar family. Five planets had always been recognised from the earliest times—viz., Mercury, Venus, Mars, Jupiter and Saturn. Who first discovered them we do not know, and certainly no one ever dreamt of looking for a sixth. It may easily be imagined with what astonishment scientific men learnt that an unknown music master in Bath had found a new child for Father Sol, and no puny infant either, for the newcomer was more than sixty times the bulk of the earth. It is true he was rather a shy youngster, for he followed his own course, nearly twice as far away as his nearest big brother, Saturn. The "little stranger" was christened "Uranus."

As very often happens, the arrival of the new baby completely upset Herschel's household. He was summoned to Windsor by the King, who created him his own astronomer, and provided him with a house and salary. His devoted sister Caroline and all the *lares et penates* were presently housed in a new abode, and Bath saw her organist and music master

no more. Herschel had sacrificed a much bigger income for the paltry £200 a year that the King allowed him, but he did not grudge the loss, for now he was able to devote himself entirely to astronomy, and to enjoy complete freedom from the treadmill of music lessons, pump-room concerts and choir practices. It is true he had to eke out his slender income by making telescopes for sale, until an influential friend managed to get the King's ear and induce His Majesty to provide the funds for a new and much more efficient telescope for Herschel's own use. This instrument ultimately cost over £4,000.

Herschel's first exploit with the new telescope was to provide "Uranus" with a couple of moons to bear him company in his far-off wanderings, and to add two more to the five Satellites that Saturn was known to possess.

Then another important event took place—in his own family this time—he married a lady who not only thoroughly sympathised with her husband's work, but, by her wealth, relieved him from all monetary worries. After his marriage he moved into a much more commodious house at Slough, where he lived for the remainder of his life.

Nebulæ and Double Stars.—The amount of work Herschel got through during his life at Slough was prodigious. He discovered over 2,500 nebulæ and star clusters, and in one region of the "Milky Way" he suddenly met with an exceedingly dark area, as if the whole stellar universe had been pierced by a gigantic hole. "Surely there is a hole in the heavens!" he exclaimed to his sister, but he had no explanation to offer of this extraordinary phenomenon. Modern astronomers have come to believe that these dark patches are due to gigantic clouds of cosmic dust, blocking off the light of the stars beyond them.

Herschel catalogued over 800 "double stars," as they are called. In some cases he noticed that in these paired stars one was much fainter than the other, which, for that reason, he thought must be much farther away. He tried to determine the parallax of the brighter of the two as against the other, but he could discover no shift after an interval of six months. But he did find that both were as large as, if not

larger than, our own sun, and revolved round each other, just as the thumbs may be made to revolve when the fingers are interlaced—" twiddling," as it is often called.

Drift of the Solar System.—Perhaps the most sensational discovery Herschel made was that our whole solar system, the sun with all his attendant planets and their satellites is moving through space. Where to? Even that profound question Herschel was able to answer. If we should happen to be at sea at night and approaching a harbour, the entrance to which is marked by two lighthouses, while still at a great distance off the two lights may appear only as one, but as we gradually approach the harbour the single light resolves itself into two, at first quite close together, but slowly diverging, until, when we near the entrance, they stand right and left.

Now in one very far distant constellation called " Hercules," Herschel, after prolonged watching, noticed that the intervals between certain stars appeared to be slowly widening, and that observation suggested to him that our little system was gradually travelling towards the diverging stars in " Hercules." The story is not quite so simple as it looks, but it was a bold guess on Herschel's part, and our modern astronomers have nothing to say against it.

Think what a change had taken place in the conception of the heavens since the days, only 150 years before, when Galileo was content with proving that the earth went round the sun, to his own satisfaction at least, if not to the minds of those who were too ignorant or too prejudiced to see " the vision of the world and all the wonder that would be." Herschel had truly founded a " Science of the Stars."

Sir John Herschel.—In 1792 a son was born to Sir William Herschel, who many years later became also a great astronomer, though overshadowed to a large extent by his more distinguished father. Sir John Herschel, as he ultimately became, followed closely in his father's footsteps, and " swept the heavens " of the southern hemisphere as Sir William had done the northern, living for several years in South Africa for the purpose. In addition to charting over 2,000 double stars he made a careful study of two enormous masses of what looked

like luminous vapour which were visible only in the southern skies, known as the "Magellanic clouds," and which he found to be composed of groups of stars of all sizes, nebulæ, and a general luminous dust, the nature of which his 18-inch reflector was unable to reveal.

One of Sir John's most useful pieces of work was the writing of a general account of all that was then known about the heavens in language that anyone could understand, and thus he enabled the general public to learn something of the wonders that had been discovered.

After the enormous strides that had been made in our knowledge of the heavens during the seventeenth and eighteenth centuries, it is not to be wondered at that there were not a few philosophers who longed to have some reliable theory that would explain how all these systems of worlds came into being. They must have had a beginning, and if so, what was that beginning like? Would they last for ever, or would there be an end some day, and what kind of an end would it be?

Cosmogenesis—LAPLACE.—There was one great genius, a Frenchman, who was younger than Sir William Herschel, and who made an effort to answer these questions. His name was Pierre Simon, the son of a small farmer near Honfleur, on the Seine, opposite Havre. Towards the end of his life he became a very distinguished man of affairs under the great Napoleon, and was ultimately ennobled as the Marquis de Laplace. Laplace is best known by his two famous books, the "Système du Monde," or the "Theory of the Earth," published in 1796, and the "Mécanique Céleste," or the "Mechanics of the Heavens," which appeared in 1799. Since the "Mechanics," as a distinguished modern astronomer has said, is "one of the most difficult books to understand that has ever been written," we shall leave it severely alone. No one need attempt to read it who has not been naturally gifted with a mathematical brain, highly polished by constant use. The other book was much simpler both in its matter and its style; and in it Laplace sketched out the story of our solar system as he imagined it, a story which we always call Laplace's "Nebular Theory."

Without troubling ourselves with the mathematics of the question at all, we shall have no difficulty in grasping the theory after having mastered the general construction of the solar system, as we know it now. Fig. 42 is a plan of the solar system from the sun to the orbit of Saturn, the orbits of the various planets being approximately at their relative distances from each other. The numbers below the initial letters of the planets are their mean distances from the sun in millions of miles, any fraction over half a million being taken as one. On studying the figure it will be seen that there is a wide gap between the orbit of Mars and that of Jupiter, and the astronomers of the eighteenth century often speculated on the possibility

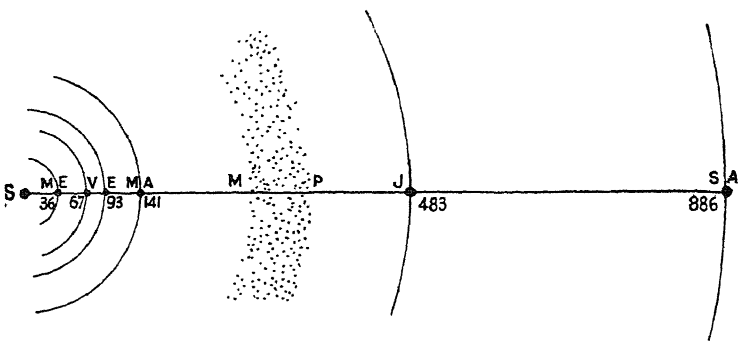

FIG. 42.—SOLAR SYSTEM AS FAR AS SATURN.

Nos. in millions of miles of distance from the Sun. S, Sun; ME, Mercury; V, Venus; E, Earth; MA, Mars; MP, Minor planets or asteroids; J, Jupiter; SA, Saturn.

of there being another planet circling in the vacant space. One of these astronomers, a contemporary of Herschel, called Bode, noticed a peculiar fact. In the simple sequence of numbers 0, 3, 6, 12, 24, 48, 96, each (save the second, of course) being double the number preceding it, when now 4 is added to each of these numbers the sequence 4, 7, 10, 16, 28, 52, 100 is obtained. Comparing these figures with those of the *relative* distances of the planets from the sun—viz., Mercury 3·9, Venus 7·2, Earth 10, Mars 15·2, Jupiter 52·9, and Saturn 95·4—it will be noted that they correspond very closely with the sequence 4, 7, 10, etc., with one exception—there is

nothing to represent the sequence number 28. This sequence-relationship came to be called "Bode's Law."

The Asteroids.—Was there a planet missing? Search was made, but in vain, for several years until in 1801 an Italian observer, named Piazzi, discovered a tiny little object that moved like a planet, but whose diameter was only 485 miles, or about a quarter of that of our moon. This minute body was called "Ceres." If the classical deity after whom this little planet was named be the goddess of plenty, her namesake in the heavens was to be the forerunner of an abundant crop of brothers and sisters, for at the beginning of the twentieth century we knew of well over a thousand of these "asteroids," or tiny planets, whirling round the sun in a majestic zone, between the orbits of Mars and Jupiter.

Relative Sizes of the Planets.—So much for the relative positions or distances of the planets from the sun; there is left for consideration their relative sizes. Fig. 43 represents their circumferences drawn roughly to scale, one within the other. The dotted line represents the relative size of Neptune, not discovered until long after the time of which we are speaking. Of course, we cannot represent the sun, for he would require a circle nearly two feet in diameter if drawn on the same scale. The earth is about 8,000 miles in diameter, Jupiter 86,500 miles, while the sun is more than ten times that—viz., 866,000 miles, which means that Jupiter is a thousand times and the sun a million times the bulk of the earth. Yet, in the days of Galileo, people quite seriously believed that this insignificant fragment was the centre of creation, and that all the rest was

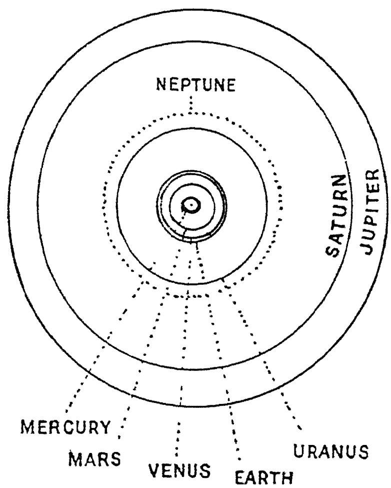

FIG. 43.—RELATIVE DIAMETERS OF THE PLANETS.

manufactured for its benefit! Such was the colossal egotism of the geocentric cosmogony!

The Nebular Hypothesis.—Let us turn now to Laplace's dream of how all this great system of worlds came into being. He imagined that the solar system originated in a nebula, *i.e.*, one vast cloud of gas, hundreds of millions of miles across, at a temperature far, far higher than any electric furnace that we have as yet devised can reach, so hot, indeed, that a metal like iron could exist only in the form of a vapour. Further, he thought of this vast cloud as rotating with a speed which increased as it contracted by cooling. In the course of eons of time, this huge cloud, as it cooled, began to condense, most of it into a central denser core, the rest forming a gigantic but still gaseous envelope which flattened owing to centrifugal action. The latter effect increased as the speed of rotation increased till at a critical point matter was thrown off the outer edge of the disc-like nebula, and this process led to the detachment of separate condensations by repetition of centrifugal effect. Circling round the central fire, and each of them, at the same time, spinning on its own axis, all these condensations moved in the same direction and by repetition of the centrifugal process gave rise to secondary condensations or satellites. The sun thus spins on its axis once in twenty-six days; the earth rotates on its axis once in twenty-four hours, and all the other planets follow suit, all, with only minor exceptions, rotating and revolving in the same direction.

By and by these condensations began to lose some of their heat, and became first liquid and then solid, and formed the planets and moons of our solar system, while the great central mass, being so vastly larger, retained much of its primeval heat, with a semi-gaseous consistence (for it is now only about one and a half times as dense as water), and became our sun. On that hypothesis the great zone of asteroids between Mars and Jupiter would represent a ring of material which, instead of condensing into one planet, aggregated into several hundreds of smaller ones, comparatively so minute that it has taken more than a century for our best astronomers to count them all, if they have completed the tally even yet.

If this were the true story of the origin of our solar system, the same sort of thing may be supposed to occur all through the universe, although in our brief span of life we could not hope to watch the actual making of another solar system. As a matter of fact this brilliant hypothesis is known to be erroneous so far as the origin of our solar system is concerned, and Laplace's theory may be described as a dream, but it may be a dream that, in some form, is a reality in many a yet unexplored corner of the "boundless universe" (see p. 332).

The Discovery of "Neptune."—Let us imagine an onlooker sitting in the gallery of a large public hall, watching the movements of the crowd below. Presently he notices a newcomer entering the doorway, who, after a pause, recognises, at the other end of the hall, a friend with whom he very much desires to talk. On account of the crowded floor he cannot reach his friend by pushing forward in a straight line; someone collides with him on one side, another on another side, or he turns aside for a moment to shake hands with an acquaintance, but he gets to his destination in the long run. From his seat in the gallery our observer can watch his progress and see for what point he is steering, although his path is by no means a straight one, as it might be if all the other people in the crowd were blotted out. Now let the onlooker imagine that he sees only the person he is interested in, and none of the other jostling folks, who may be supposed to be wearing the "helmet of Orcus" that gave invisibility to anyone who wore it. He might very well be puzzled to understand why his friend did not move in a straight line without constantly wobbling from side to side in such an erratic manner. The bearing of this simile will appear presently.

We have just seen how Herschel discovered, almost by accident, the new planet "Uranus," majestically pursuing his long journey of nearly 6,000 million miles round the sun, a journey that took him eighty-four years to complete. Of course, after the discovery of Uranus the eyes of astronomers all over the world were fixed on him, in the hope of determining his exact size, his peculiar characteristics—if he had any—the speed at which he moved, and so on.

One of the points that had to be decided was his exact path or orbit.

Astronomers had for many years been charting the heavens, marking the precise positions of every star that their telescopes disclosed, so, when Uranus was discovered, it naturally occurred to the "Watchers of the Skies" to look up the old maps to see whether the position of Uranus had been recorded before, without any astronomer having dreamt that it was a planet and not a star. There was one old chart, dating from 1690, preserved in the observatory at Greenwich, that gave a picture of the heavens in the region where Uranus might have been then, and there was one star in particular that had attracted the attention of Flamsteed, at that time Astronomer Royal, but when it was looked for, behold! it had vanished. It had wandered out of the field. The natural conclusion was that this was the new member of the solar system that had been discovered by Herschel. Flamsteed had seen it several times, but, alas! he had failed to recognise it as a planet. Small blame to him, for another astronomer, Lemonnier, had also seen and recorded it in his charts at least a dozen times, and yet had failed to identify its real nature.

When Uranus was welcomed into the circle of our solar system, it became of great importance to plot out its course in the heavens and see whether it also obeyed Newton's law of universal gravitation. This was a very laborious task, for no one man could hope to follow the new member of the family throughout an entire journey of eighty-four years' duration. Still, the observations were made and the orbit of Uranus was plotted out, but when this had been done, lo and behold! instead of following the pathway the astronomers had laid out for him, he declined to follow it, any more than the visitor took the path he was expected to take towards his friend in the assembly hall. Was Uranus disobeying Newton's law? When all the persons in the hall wore the "helmet of Orcus" it was impossible to see them, but the erratic course the visitor followed in his effort to cross the hall could be followed. One could only conclude that there must have been something enticing or pulling him over to one side or the other. So it

began to be realised that there must be something disturbing Uranus, some boon companion holding out a hand of good fellowship as he passed him by.

Instead of peering through telescopes looking for the unknown who wore the "helmet of Orcus," two mathematicians collected all the information they could find about Uranus's vagaries and, using their mathematical skill, sat down in their studies and attempted to find out what the attraction was that made the planet deviate from the path he ought to have followed. These vagaries were called the "Perturbations of Uranus," and they had perturbed the minds of the astronomers of the early years of the nineteenth century very much indeed. The two astronomer mathematicians were John Couch Adams, a young graduate of Cambridge, and U. J. J. Le Verrier, the director of the Paris Observatory. Both started to solve the puzzle, each quite ignorant of what the other was doing. The story of the struggle for the first place in the race is an interesting one.

Adams began his research soon after he had taken his degree in 1843, when he was only twenty-four years of age, and two years later he had solved the problem by mathematical reasoning alone. He found that the cause of Uranus's wanderings from his proper path must be the pull of yet another planet far beyond the orbit of Uranus, which as yet wore the "helmet of Orcus," for it had never been seen, or at least had never been recognised as a planet. Having worked out its orbit and fixed on the spot in the heavens where it was most likely to be found, Adams told his story to the then Astronomer Royal, Sir George Airy, in October, 1845, and asked him to search the heavens for the unknown; but this could only be done by comparing the telescopic field with a chart of the stars in the same region, and such a chart was not available.

Meanwhile Le Verrier's attention had been drawn to the same eccentricities of Uranus, and by June, 1846, he also, by mathematical reasoning alone, had decided that some disturbing planet must exist. His results, when they were published, thoroughly startled the authorities at Greenwich, for

the position that Le Verrier gave for the stranger was within a degree of that which Adams had predicted nine months before. That two men, working quite independently of each other and on the same material, should have come to the same result was felt to be something more than a mere coincidence, so Airy asked Challis, at that time professor of astronomy at Cambridge, to map out the region of the heavens in which Adams had said the unknown planet would be found. Galle, the head of the Berlin Observatory, was invited by Le Verrier to explore the same region. Galle already possessed what Challis was only in the act of making—a chart of the star area in question. It may be imagined with what anxiety Galle unrolled his map and checked off every star in the field of his telescope with those in the corresponding section of his map. At last one bright uncharted spot was noticed, and on the following night it was still there—but it had moved! There was no longer any doubt about it; here was the unknown, who had at last taken off his helmet of invisibility.

A controversy at once arose between the French and British astronomers as to which of the two men belonged the credit of the great discovery. Now, both sides are content to say "honours even," and to agree in christening this, once supposed last, addition to the family circle by the name of "Neptune." We know much more about him now; he takes twice as long as Uranus to girdle his parent Sun; he is a little larger than Uranus, but less than half the diameter of Jupiter. As Neptune is 2,800 millions of miles distant from the Sun, which is 30 times the earth's mean distance, it will be seen that this planet does not conform to Bode's Law (p. 82) which requires about 38 times the distance. Uranus, however, conforms approximately.

After the excitement caused by the discovery of Neptune had died down, nothing of much importance took place in astronomy for some time. She was waiting for her next great advance until her sister sciences, physics and chemistry, had provided her with new instruments wherewith to probe the depths of space. We may therefore make use of the pause to turn to the other sciences and see what progress they had made since the days when Newton wrote his immortal work, the "Principia."

§ ii. Geology

At the beginning of the eighteenth century, geology, the study of the earth's crust and its partial covering of ocean, was in a very backward state. Men like Buffon speculated vaguely about the origin and history of the world long before enough was known about its structure to justify any conclusions on the subject. The foundations of the science had yet to be laid, and fortunately the new century saw the rise of a new class of observers who contented themselves with collecting data, leaving speculations to the future.

The Foundations of Geology—Guettard.—One of these was a man whose services to the science have been rather ignored, perhaps because he was shy and retiring by nature, and because his discoveries did not shine out with the brightness that made a halo round the names of the finders of new planets in the solar system. This man was Jean Étienne Guettard, an apothecary in Étampes, a village a few miles from Paris. He was born in 1715, and, as a boy, was a very keen naturalist, never so happy as when he was collecting plants and watching the changes taking place in the rocks and soils on which they grew. About that time the science of botany was moving forward under the care of De Jussieu, and, owing to his influence, young Guettard was appointed curator of the fine natural history collection that had been made by the Duke of Orleans.

During his wanderings over Western Europe in search of plants, Guettard soon realised that their occurrence depended largely on the nature of the soil and rock in the neighbourhood, and thus he was more and more drawn away from the study of the plants themselves to that of the rocks which lay beneath them. He became, in short, a mineralogist, and began to record the occurrence of rocks of the same kind in different parts of the same country. It should be remembered that the very word "geology" was not then in use; it was invented some fifty years later by another distinguished observer named De Saussure, of whom more anon.

Guettard, in his study of the rocks, did not fail to note the fossils that lay embedded in them, and he was under no misapprehension as to how they found their way there. He held that they were precisely what they appeared to be—viz., the petrified remains of plants and animals that had lived on the surface of the earth at the time these rocks had been formed.

Geological Maps.—Guettard was among the first to make a map showing the way in which the different kinds of rock were distributed over France, the forerunner of the geological maps with which we are so familiar, and issued from time to time by the Geological Surveys of different countries. There were no political divisions in Guettard's maps; all he was concerned with was the distribution of the same kind of rock, whether in France, Germany, Belgium or Britain. His work on fossils was particularly important, because he held, and rightly, that these remains were the key to the past history of the earth. Indeed, he looked on the earth's crust as a vast cemetery wherein lay buried the remains of the ancestors of the beings now living on its surface. One of his papers bore the quaint title, "On the accidents that have befallen Fossil Shells compared with those which are found to happen to Shells now living in the Sea," and that title really suggests the lesson that modern geology teaches—viz., that, in order to know what happened in the past, it is essential to study what is happening now. Another of his papers was "On the Degradation of Mountains effected in our time by Heavy Rains, Rivers and the Sea," and that is precisely what the old Greek philosopher, Pythagoras, taught more than 500 years before our era. Great credit is due to the Frenchman who thus turned men's minds from fancy back to fact, from guesswork to reality.

The Volcanoes of Auvergne.—Guettard was the first to explain the nature and origin of the strangely shaped mountains known as "The Auvergne" in southern France, not far from Clermont. One day he was wandering near that region and noticed that the milestones were made of a sort of black rock which he thought must be of volcanic origin, and, as he followed them on his journey, he found that the villages began to be built of the same material. Asking where the rock had come from,

he was told from a quarry some ten miles distant. Sure enough, when he got there he found it was a quarry of lava, and with great perseverance he at last located the cone and crater of an old volcano. Hence he concluded that this quiet pastoral country had, in days long gone by, been the scene of tremendous disturbances, when glowing mountains belched forth streams of molten rock, as Vesuvius and Etna were doing at the moment, although he had never seen them. He could not get

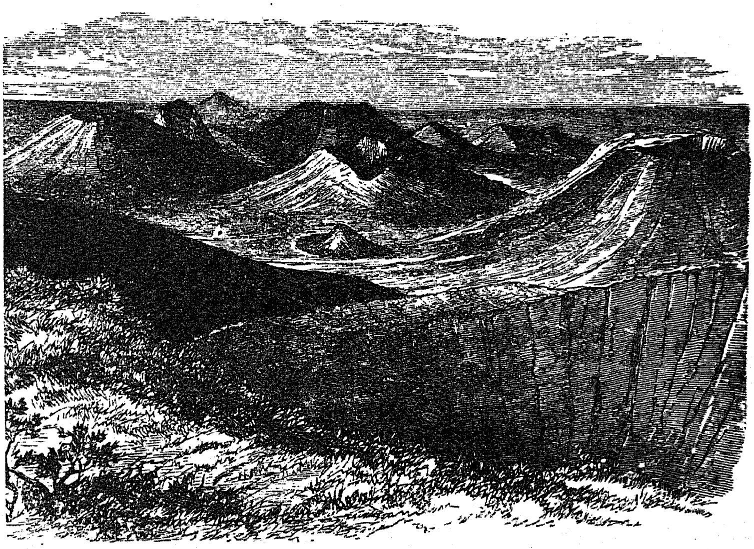

FIG. 44.—THE VOLCANOES OF THE AUVERGNE.
From Geikie's "Text-Book of Geology," Vol. I., by kind permission of Macmillan and Co., Ltd.

rid of the old idea, however, that the cause of all this volcanic activity was the burning of coal, petroleum and other combustibles deep down in the earth's crust, and in support of his view pointed to the beds of asphalt at Clermont.

The Nature and Origin of Basalt—DESMAREST.—Another geological pioneer, also a Frenchman and a contemporary of Guettard, was Nicholas Desmarest, who was born in 1725, near Brienne. His parents were extremely poor, so poor, indeed, that had not Nicholas been practically adopted by the Catholic

Seminary at Troyes, he would never have been educated at all, for it is said that he could hardly read when he was fifteen years old. After ten years of drudgery spent in teaching what he had learnt at Troyes, he competed for a prize offered for the best essay on the question whether England had ever been geologically united to France. He won the prize and, as a consequence, made the acquaintance of the famous mathematician D'Alembert, who in turn introduced him to the Duc de Rochefoucault, who proved himself a warm friend and patron of the young geologist. Owing to the powerful influence of this

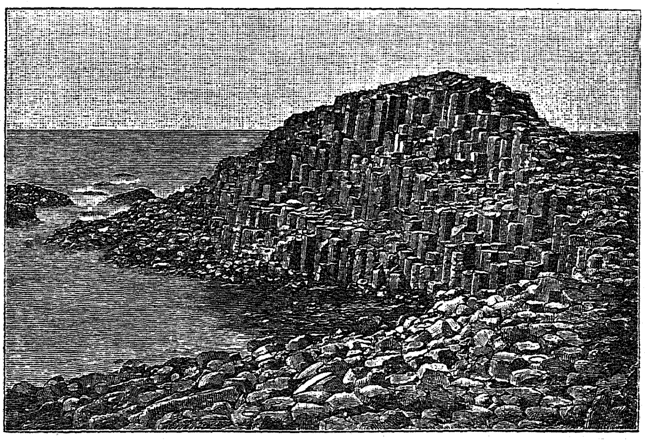

FIG. 45.—THE HONEYCOMB, GIANT'S CAUSEWAY.
From "Chambers's Encyclopædia," by permission.

nobleman, Desmarest was ultimately made a Director of Manufactures, but only just escaped the fate of his benefactor in the perilous days of the Revolution.

When peace returned to the troubled country, Desmarest followed in Guettard's steps and wandered over the land, adding to his geological knowledge, until he found himself in Auvergne, the scene of Guettard's labours a dozen years before. There he set himself the task of working out the nature and origin of the curious black stone so common in France and other parts of Europe, and occurring frequently in erect polygonal columns, familiar to us in Britain in the Giant's Causeway and in the

island of Staffa off the west coast of Scotland. The real difficulty in interpreting this remarkable formation lay in the fact that it was to be found wedged in between layers of rock that had undoubtedly been laid down in the sea. He noticed that this "basalt," as it was called, from an old name given to it by the Roman historian, Pliny, often occurred in isolated patches, lying far apart from each other, and the conclusion he came to was that all these patches had at one time formed a continuous sheet of lava, but had subsequently been cut into fragments by the constant erosion of rivers. He thus laid still further stress on the doctrine of denudation that is now emphasised in every textbook of geology.

Desmarest was most conservative in his habits. He always rose, had his meals, and went to bed at the same hours, and never changed the cut of his clothes all his life long. Perhaps this extreme regularity in his habits, and the fact that he spent so much of his time in the open air collecting material for his writings, explain why he lived to the advanced age of ninety, without ever having had a serious illness.

The Geology of the Alps—H. B. DE SAUSSURE.—Everyone who has visited Switzerland or has seen photographs of its magnificent scenery can visualise its lofty snow-clad mountains with glaciers or rivers of ice sliding slowly but unceasingly down the higher valleys, with turbulent muddy streams of ice-cold water issuing from under their lower ends. Amid such surroundings was born, at Geneva, in 1740, Horace Benedict de Saussure. He must have been a precocious youth, for, after a brilliant university career, he became a professor before he was twenty-two. His tastes at first lay in the science of botany, but he soon branched off into geology and mineralogy, and it was he who first christened the science of the history of the earth's crust by the name by which we now know it—viz., Geology.

It was impossible for him to live amongst such scenery without feeling the lure of the mountains, and to him belongs the credit of having been the first to travel over and explore them from end to end, and not merely to view them from a distance. Listen to his own words expressing the feelings of the naturalist who dares to leave the beaten track in the valley

and climb some of the jagged peaks that soar 10,000 feet or more above him.

"Many a time, the naturalist, when almost within reach of a summit on which he eagerly longs to stand, may doubt whether he has strength enough left to gain it, or whether he can surmount the precipices which guard its approaches. But the keen fresh air which he breathes makes a balm to flow in his veins that restores him, and the expectation of the great panorama which he will enjoy, and the new truths which it will display to him renews his strength and his courage. He gains the top. His eyes, dazzled and drawn equally in every direction, at first know not where to fix themselves. By degrees he grows accustomed to this great light, makes choice of the objects that should chiefly occupy his attention, and determines the order to be followed in observing them. But what words can describe the sensations or the ideas with which the sublime spectacle fills the soul of the philosopher? Standing as it were above the globe, he seems to discover the forces that move it—at least, he recognises the principal agents that effect its revolutions."

It is curious to note how De Saussure clings to the old ideas about the origin of rocks. There were many geologists of his time who held that the granite that formed the backbone, so to speak, of the mountain mass of the Alps, was first deposited in the sea and afterwards crystallised, and that the sheets of limestone and other strata that lay against the flanks of the ridges were formed in that position. Although at first De Saussure held such views, he changed his mind later on, and admitted that these tilted layers could not contain sand and water-worn pebbles unless they had been formed horizontally at first and subsequently upheaved. The only explanation that would account for such elevation was the old one of vast internal volcanic fires, but he rejected it because he could find "neither mineral nor stone which might be suspected to have undergone the action of these fires." He began to picture a series of rock masses, in part at least deposited in successive layers, and then, owing to the contraction of the earth's crust, bent into wave-like folds, "as a number of heavy

carpets laid one on another would be if their opposite ends were pushed nearer together." Occasionally the thrust is so powerful that the folds are bent over in the opposite direction (Fig. 46, JL, L, T); sometimes the rock masses are even broken under the strain, and the upper part of the fold slides forwards over the under (L). Then over and above all this squeezing and folding comes the action of rain, avalanches and glaciers, relentlessly scouring out valleys and scouring the mountain sides, while frost is for ever wedging off fragments and boulders of every conceivable size and shape to form more and more polishing powder wherewith the glaciers and the rivers may grind the primeval mountain forms into their present shapes, and deposit

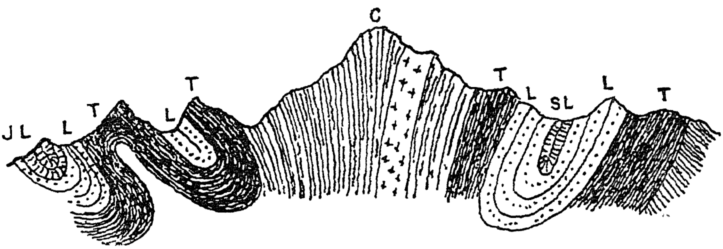

FIG. 46.—SECTION THROUGH MONT BLANC, SHOWING CRYSTALLINE ROCK, C, WITH TILTED AND FOLDED SEDIMENTARY STRATA ON EITHER SIDE. (AFTER SIR A. GEIKIE.)

JL, Jurassic limestone; L, Lias; T, Trias.

the debris, grain by grain and pebble by pebble, on the floor of the ocean. It was this operation that most attracted De Saussure's attention, and it is to his vivid description of this slow but never-ceasing erosion of the mountains that we owe so clear a conception of what we nowadays call "Denudation."

The Theory of the Earth—HUTTON.—As Newton with his law of universal gravitation struck the keynote of all further progress in astronomy, so James Hutton settled for all time the lines of advance in geology, and the text of his sermon was: "What is happening now happened in the past." Hutton was born in 1726, and was the son of the Treasurer of the City of Edinburgh. After taking a degree in medicine, he devoted himself to the study of chemistry with the view of becoming a scientific farmer. He settled on a farm in Norfolk where he examined chemically

not only the nature of the soils on which he grew his crops, but also the peculiarities of the underlying rocks from which these soils were largely derived. In 1754 he returned to the neighbourhood of his native city and proceeded to cultivate a small estate he had inherited from his father. During the next fourteen years he studied deeply the various problems that were being discussed by the French geologists of the day. As more and more of his time was given up to these pursuits he felt himself obliged to let his farm and transfer his abode to Edinburgh, where he became an intimate friend of the then professor of chemistry, Joseph Black. For more than a quarter of a century Hutton patiently worked through all the treatises he could find on geological subjects, and checked the statements in them by his own observations made in the rich fields offered to him round Edinburgh and in other parts of the British Isles. Many papers on special points came from his pen, and one of these was a general outline of earth structure, which was read to the Royal Society of Edinburgh. This society was founded in 1783, largely owing to his efforts along with those of his friend Black, a society which represented in the Scottish capital what the older Royal Society stood for in London. In 1795 Hutton published his great work called "A Theory of the Earth," only two years before he died.

Although this work is now regarded as a classic in science, it was not a very readable book, for his style of writing left much to be desired, and he did not always arrange his facts in such a manner as to carry conviction to his readers. Fortunately for him and for the science he had an intimate friend and enthusiastic admirer in the Rev. John Playfair, Minister of Benire, near Dundee. Playfair was not only an able clergyman of the Church of Scotland, but also a mathematician and geologist of considerable repute; indeed, his attainments in these subjects were so marked that he became professor of mathematics and, later, of natural philosophy, as physics is called in the northern universities. Realising the difficulties people had in following Hutton's arguments as expounded in the "Theory," he took upon himself the task of writing what might almost be called a translation of it which he published

in 1802, after Hutton's death, under the modest title of "Illustrations of the Huttonian Theory of the Earth." Our distinguished modern geologist, not long since dead, Sir Archibald Geikie, describes this book as a "consummate masterpiece." What Hutton's views on earth structure were may be most easily grasped by a study of Playfair's admirable summary.

Hutton's general thesis is that there is "nothing new under the sun"; what is taking place today is just what took place in days gone by, although perhaps in some respect more vigorously. Below the soil on which we grow our crops and build our cities lie beds of sandstone, limestone, shale, or gravel, all derived from the waste of mountains and lower lands, carried down by rivers and deposited on the bed of the ocean. We see this going on now, and so it must have been when there was no human eye to see it. The rocks we clamber over today are only the consolidated sediments from the rivers of the past, solidified by the weight of superincumbent layers laid down on them from age to age. Hence Hutton recognised primary rocks and lying over them, secondary, all baked by subterranean heat, and squeezed or crushed into cakes or strata. These strata, once horizontal (Fig. 47), afterwards became bent, twisted, folded and tilted up on end by internal convulsions of nature, long eons ago, convulsions which Hutton believed were due to some gigantic forces emanating from the molten interior of the earth. What these might be he did not venture to suggest, holding that geology was not concerned with the origin of things, but only with things as they are.

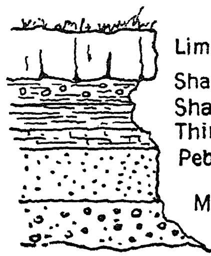

FIG. 47.—HORIZONTAL STRATA ON A CLIFF FACE (AFTER SIR A. GEIKIE.)

But there were other kinds of rocks that did not appear to have been laid down in beds, and he fancied that these had been originally molten and pressed in between primary and secondary

strata while the bending and folding was taking place, so producing very distinct changes in the stratified rocks into which they had been forced. Granite, he thought, was such a rock, not deposited in the sea and then crystallised, as some believed, but a rock formed in some way by the agency of fire.

The next important principle that Hutton emphasised was the perpetual wearing away of mountains and hills by rivers that carried off fragments, from microscopic size up to stones or even boulders, scraping the sides of the valleys, lowering the summits of the mountains inch by inch, and spreading all the debris over the bed of the ocean. When glaciers were the agents they were able to transport on their surfaces much larger masses that had tumbled on them from the cliffs above, and might carry them for many miles away from their original home, where they might be stranded by the melting of the ice, and left on a land totally different, geologically, from that which gave them birth. These boulders are what we call " erratics," or wanderers. This was a subject very fully worked out in later years.

Stratigraphical Geology, and Palæontology—W. Smith.—Towards the end of the eighteenth century two subjects of great importance began to occupy the minds of geologists; the one was the order or sequence in which the rocks had been laid down in the past history of the earth, and the other was the nature of the fossils that were found imbedded in them. The two subjects were very soon discovered to be closely linked together; indeed, erelong it was seen that a close study of the fossils would provide the key to the succession of the rocks. There were two districts where such a succession could be traced without much difficulty, for in these regions the layering of the strata had not been nearly so much disturbed in bygone ages. These districts were Central France and Eastern England.

Take, for example, an imaginary section across England from Snowdon to the Wash (Fig. 48). In North Wales we find the very oldest rocks tossed up into high mountains (P); then follows a rather steeply inclined set of beds in which we find coal (C), and then a broad flat plain, represented on our ordinary maps by the counties of Cheshire and Shropshire

(NRS). The coal measures appear again when we approach the Derbyshire hills, while away eastwards are low-lying almost horizontal strata, gently tilted towards the west and ending in the plains of Lincoln and Norfolk. It will be seen, therefore, that a traveller walking from Yarmouth to Holyhead passes over successively older rocks, since the more recent (overlying) strata have been worn away to a greater extent towards the west.

But the strata are by no means so simply arranged in other parts of the country, and the problem for the geologist is to say what is the order of succession where the layers are bent, twisted, and overturned, or even largely worn away, so that only fragments of them are left, jumbled up with other layers

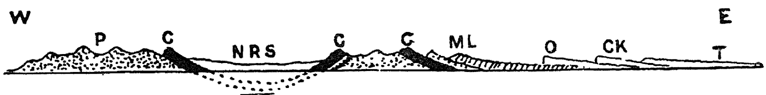

FIG. 48.—SECTION ACROSS ENGLAND FROM WALES TO NORFOLK. (AFTER SIR A. C. RAMSAY.)

in great confusion. Let us now see how the fossils may help us. Suppose we meet with a bed of rock containing shells that are quite unknown to the student of living Mollusca, and another bed containing the same forms, but with a sprinkling of new ones rather more like those now living. In another layer still the old types of shell appear to be dying out, for only a few scattered examples can be found, while what we may call the second type are abundant. The next layer contains plentiful specimens of the second type, but mixed with a third set still more closely resembling living forms, but the first type has disappeared altogether. Obviously, if we should meet with rocks in any other part of the country containing fossils all belonging to the first type, we should be justified in saying that these rocks were of the same geological age as those in which we first identified them, and similarly for the other two kinds of strata. In this way, then, we might be able to trace a particular bed of rock all over the kingdom, even though these fragments might be many miles apart. For example, in the section given in Fig. 49, taken across Merionethshire from

Tremadoc Bay to the vicinity of Bala Lake, the beds marked A contain well-marked fossils, and across country miles away we meet with another bed of rock, A′, in which such fossils also occur. We have no hesitation in saying that A and A′ are outcrops of the same stratum, but that long ages of denudation have swept away all the connecting parts from the top of what must have been once an immense hump or "anticline," as the geologists call it, represented by the dotted lines.

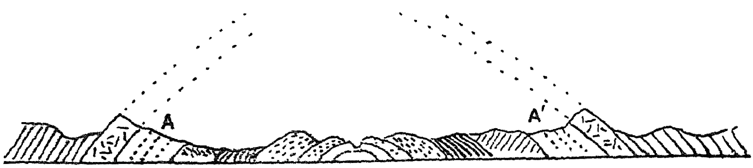

FIG. 49.—SECTION ACROSS MERIONETHSHIRE. (AFTER SIR A. C. RAMSAY.)

There were many at the end of the eighteenth and the beginning of the nineteenth centuries who worked at problems such as these, tracing the occurrence of similar rocks all over the kingdom and mapping them out with great patience and skill. One of these pioneers was an Oxfordshire man called William Smith. He was born in 1769, and, after receiving a rather scanty education, became an assistant to a land surveyor. His duties took him to every part of the kingdom, and being greatly interested in geology, he made abundant notes of everything that might have a bearing on the succession of strata. It was not long before he became certain in his own mind that there was such a succession and that each layer contained fossils special to itself, which would enable it to be traced wherever it might occur. After collecting quite a mass of data, he plotted out his results in the form of a geological map, one of the first ever produced for Great Britain. Although he published little else, still Smith must be remembered as a pioneer in what is now called stratigraphical geology.

Both before and after Smith's day the workers in the subject increased rapidly, and data were accumulating to such an extent that it soon became possible to exhibit the whole series

of rocks in the order of their ages in the form of a table (Fig. 50).

The Primary Rocks—MURCHISON, SEDGWICK, RAMSAY.—The most ancient, or Primary, rocks were studied by men like Sir Roderick Murchison, who devoted himself to a series of very ancient deposits on the borders of Wales which he called Silurian, after the tribe of the Silures who inhabited that region in Roman times. The results of his work were published in 1838 in a huge volume of over 800 pages, along with an atlas of plates of fossils and sections showing the distribution of the beds.

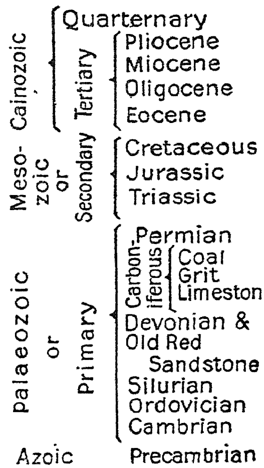

FIG. 50.

Murchison was closely connected in his researches with another distinguished geologist, Adam Sedgwick, a Yorkshireman, who was born in 1785, in the Vale of Dent, where his father was vicar. When he became professor of geology at Cambridge he had only a scanty knowledge of his subject, but what he lacked he soon acquired by an enthusiastic study of the very complex geology of the Lake District, where he discovered the presence of volcanic rocks wedged in between layers that had obviously been laid down in the sea. It is to him that we owe much of our knowledge of the rocks lying immediately above the Silurian, called the Devonian and Old Red Sandstone. He also grouped together the layers below the Silurian as Cambrian, after the old name for Wales, where they were so well developed.

The tale was completed when Sir A. C. Ramsay described rocks of greater age even than the Cambrian, in which no fossils of any kind could be found, and which he called Precambrian or Azoic—*i.e.*, without life. The British Isles, it will be seen, provide us with examples of practically every kind of rock of which the earth's crust is made, and, taking into account their extent, a little over 125,000 square miles, we may say

that there is perhaps no area in the world of equal extent that can show so great a variety of geological formations.

Geological Textbooks.—The immense increase in our knowledge of the details of all these various strata during the later years of the eighteenth and the early years of the nineteenth century made it quite impossible for even an educated man to follow what had been accomplished, and to appreciate what had yet to be done, so that the student, and the general public also, hailed with joy the appearance in 1833 of the excellent summary of all that was then known on the subject, called "The Principles of Geology," from the pen of Sir Charles Lyell. Ramsay said of this book: "We collect the data and Lyell teaches us to comprehend the meaning of them." But Lyell did more than merely describe and interpret what others had discovered; he pointed out the similarity of the fossils in the most recent rocks, known as the Tertiary, with those forms at present living, and coined names to indicate the chief stages in Tertiary formations—Eocene, the dawn of the recent; Miocene, the less recent; and Pliocene, the more recent.

Ramsay also wrote an excellent account of the structure of Britain, in which he described the scenery of our islands, and showed how that scenery depended on the nature of the rocks that went to form the hills, valleys and plains. This subject, which appealed most of all to the traveller and the tourist, was, in later years, made much of by Sir Archibald Geikie, who died in 1924, after holding the chair of geology in Edinburgh University as well as the post of Director of the Geological Survey. To him we also owe the famous "Textbook of Geology" that has been the student's guide for very many years.

The Action of Glaciers—AGASSIZ.—There is another name that stands out prominently in the history of Geology, that of one who opened up an entirely new subject, whose existence had been hinted at, however, by Hutton in his "Theory of the Earth." This was Louis Agassiz. He was a Swiss by birth, but spent much of his life in the United States. Before he crossed the Atlantic he explored the Alps, and wrote the story of what he had seen, which he published in 1837. He described

how he had found "erratics," or wandering boulders, high up on the slopes of the Jura mountains, boulders which were composed of minerals that were not found in these mountains, but only in the Alps, many miles away. They lay far above the level of the glaciers that now filled the Swiss valleys, and, near these blocks, the rocks were all polished and scratched, just as were the rocks below the glaciers of his native country. He concluded that once on a time an immense sheet of ice must have spread over the plains between the Alps and the Jura, and had even climbed over the crests of the latter mountains. A glance at an atlas shows that the long ridge of the Jura, bounding the eastern margin of France, is, through most of its length, fully fifty miles distant from the Alps. The ridge in places rises to a height of over 5,000 feet, and if great masses of Alpine rock are found high up the slopes, the only means by which they could have been carried there was by ice, which must therefore have been several thousand feet in thickness. This was a sufficiently startling idea, and was at first looked at askance by many geologists; but Agassiz piled proof upon proof, until the doubters were at last convinced that his theory was correct. If so, Agassiz said it could mean only one thing—viz., that the climate of Europe at that period must have been somewhat similar to that of Greenland at the present day, where glaciers come right down to the shores of the sea.

The Great Ice Age.—Agassiz next visited the Highlands of Scotland, the Lake District and the mountains of Wales, and in all of these places he found the same evidence of glacier action where there were now no glaciers to be seen. One of the chief authorities on what is now always called "The Great Ice Age" is James Geikie, who succeeded his brother, Sir Archibald, in the Edinburgh chair, and who died a few years ago. He wrote an important book on the subject, giving all the evidence that had been collected. This unexpected phase in the history of the earth appeared just after the Pliocene period (Fig. 50), when the lower Quaternary rocks were being laid down, and seems to have affected not only Europe but the whole of the northern hemisphere, more especially Canada and the United States. What the cause of

changes of climate may be is considered later (p. 358, see also p. 485). Geologists are not even yet agreed on the subject, but what it is interesting to know is that at that time—some authorities say about 200,000 years ago—Great Britain and Ireland were connected with the Continent; there were no Straits of Dover, and it was possible to walk dryshod from the site of London to that of Boulogne or Brussels.

When the Ice Age began and the climate became colder and colder, the mountains of Britain and Scandinavia were covered with vast snow and ice fields, and glaciers streamed down the valleys and spread over the plains, until northern Britain was covered with an ice sheet which is believed to have been in some places 4,000 to 5,000 feet thick. "The whole of Northern Europe, Canada and the northern part of the United States," writes Sir Archibald Geikie, "was buried under a continuous mantle of ice. In Europe (Fig. 51) the southern edge of the ice sheet must have lain to the south of Ireland, whence it passed along the line of the Bristol Channel and thence across the south of England, keeping to the north of the valley of the Thames. The whole of the North Sea was filled with ice down to a line which ran somewhere between the coast of Essex and the present mouths of the Rhine. Eventually, and no doubt very gradually, after episodes of increase and diminution, the ice finally retired towards the north, and with it went the Arctic flora and fauna that had peopled the plains of Europe, Canada and New England. The existing snow fields and glaciers of the Pyrenees, the Alps and Norway in Europe, and of the Rocky Mountains in North America, are remnants of the great ice sheets of the Glacial Period, while the Arctic plants of the mountains, which survive also in scattered colonies in the lower grounds, are relics of the northern vegetation that once covered Europe from Norway to Spain."

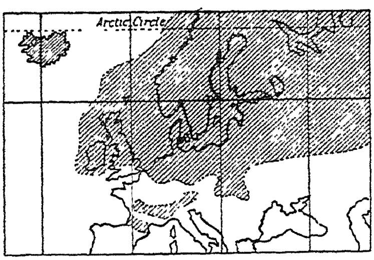

FIG. 51.—THE GREAT ICE AGE IN EUROPE.

Unless one has actually seen the great snow fields of Labrador, where Grenfell pursued his missionary labours, or the mighty glaciers that Norman Collie and his friends explored in the Selkirks, it is not easy to realise what Britain looked like in those far-off days, when "Old Father Thames," as Rudyard Kipling wrote, told the "Twenty bridges from Tower to Kew" how

> "these waters of mine
> Were once a branch of the River Rhine,
> When hundreds of miles to the East I went
> And England was joined to the Continent.
> I remember the bat-winged lizard-birds,
> The Age of Ice and the mammoth herds,
> And the giant tigers that stalked them down
> Through Regent's Park into Camden Town."

We have now brought the story of how the structure of the earth's crust was unravelled down almost to our own time, and we may leave it there and turn to the next great science, physics, and try to trace what progress it had made since Newton studied the nature of light, and Boyle discovered the law of the compressibility of gases.

§ iii. Physics

Ultra-Violet and Infra-Red Rays.—Newton, towards the end of the seventeenth century, had discovered (p. 51) that white light could be split up into a spectrum of rays of different colour—red, orange, yellow, green, blue, indigo and violet—and found that the red rays were the least bent, or refracted, and the violet most. Beyond the red on the one side and the violet on the other, no rays of any kind could be detected. More than a century later Sir William Herschel endeavoured to determine the relative heating power of the different regions of the solar spectrum by exposing thermometers in the various coloured bands. When he placed a thermometer in the path of the violet rays he obtained a slight rise in temperature, but beyond the violet there was no response at all. It was quite

otherwise with the remainder of the spectrum. As the thermometer was shifted towards the red end the temperature steadily rose, but, to his surprise, it went on rising after the red colour ceased, so that it appeared that the heat rays of the sun were mostly dark in what is now called the infra-red, beyond the limits of visibility. Herschel concluded that light rays and heat rays were of the same nature, but that while the human eye could recognise only the rays from the violet to the red, the thermometer could detect not only the visible rays but also others which were even less refracted than the red ones; and he confirmed his discovery by showing that the infra-red heat rays could be refracted and reflected by lenses and mirrors in the same way as the light rays.

Soon afterwards a physicist called Ritter discovered that the region beyond the violet, where the rays had no such heating power, was able to cause a blackening in certain compounds of silver, so that there must be rays there also, although neither the eye nor the thermometer could detect them. The word "spectrum," meaning an image or appearance, is thus a misnomer, since much of it cannot be seen at all.

Wave-Lengths in the Spectrum—HUYGENS, YOUNG.—In 1802 Thomas Young produced a very important treatise on light, in which he showed that the real difference between red and violet rays lay in their wave-lengths, and that the red rays were very nearly twice as long as the violet ones. What this means may be understood from the following simple experiment. Obtain a length of clothes-line and fasten one end to a clothes-pole or a hook in the garden wall. With the free end in the hand, stand ten or more feet away, keeping the rope fairly taut. Then move the hand up and down, when waves will be seen to run along the cord from the hand to the wall. If the hand be moved rapidly the waves will be short and the succession or "frequency" of the waves rapid, if slowly the waves will be longer and less frequent. Although we may use this analogy, heat or light waves are very different, being vibrations, not of matter, but of the hypothetical ether (p. 54) and are all exceedingly short. For instance, the length of a yellow wave is only about $\frac{1}{50000}$ inch.

Since the time of Herschel and Young we have learnt to recognise all sorts of ether waves besides those we can see and feel, not only beyond the heat waves outside the visible red, but also beyond the silver-blackening waves outside the violet. The full spectrum is thus vastly longer than Herschel or Young or any of the other workers on the subject a century ago had imagined. A glance at Fig. 52 shows what a very small part (*e*) of the entire spectrum is visible to our eyes. All the rest of it can be distinguished only with the aid of very delicate instruments specially designed for the purpose. In the figure, however, may be noted two kinds of rays: first, the X rays beyond the violet end of the visible spectrum, which are now made so much use of in surgery, and far beyond the infra-red, the radio-waves. The figures in Fig. 52 show the wave-lengths in centimetres (cm.) or metres (m.). Recently the spectrum has been extended beyond the γ-rays (Gamma) by the discovery by Millikan that the so-called "Cosmic Rays" are of excessively short-wave-length. But the way in which all these new rays were discovered must be left over for the present.

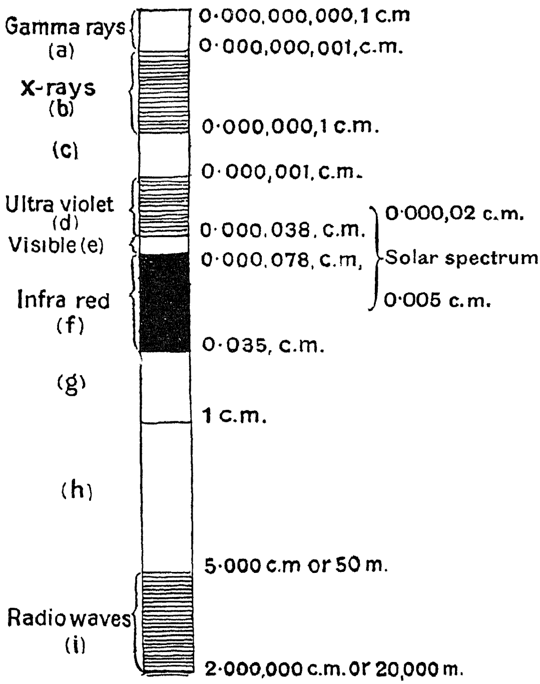

FIG. 52.—THE SPECTRUM, SHOWING THE EXTENT OF THE VISIBLE SPECTRUM AS COMPARED WITH THE REMAINDER. (AFTER HALE.)

Before leaving the subject of light in so far as it was under-

stood at the end of the seventeenth century, we must again refer to two men whose names we have already mentioned, Christian Huygens and Thomas Young.

Huygens was born in 1629 and died in 1695, so that he was a contemporary of Newton. Although intended for the legal profession, he soon showed himself as a very competent mathematician and physicist. Newton, in his efforts to make a satisfactory refracting telescope, was foiled by chromatic aberration (p. 52), and realising that the difficulties he met with were due not to defects in the lenses but to the nature of light itself, gave the matter up, and invented the reflecting telescope instead. Further, Galileo, with his very primitive instrument, failed to solve the problem of the curious triple condition of Saturn (p. 31). Huygens set himself the task of elucidating both these puzzles.

First of all, he succeeded in finding a new way of grinding and polishing lenses, and, with a much improved instrument, he was able to show that Saturn was surrounded by a ring set at an angle to the ecliptic, and which went through phases in a period of years. He was so successful with his work on lenses that he made some that were almost perfectly achromatic. He mounted these on lofty poles, giving a focus of 100 to 200 feet, the sort of instrument that Bradley used in his researches on nutation (p. 74). Huygens's greatest discovery had to do with light, and we have seen how he replaced Newton's "corpuscular theory" with the "undulatory theory" that is always associated with his name (p. 54).

Another feat performed by Huygens was the interpretation of the refraction of rays of light when they passed from a less dense into a more dense medium, such as from air into glass, in terms of his undulatory theory, and this is the explanation he gave. When a wave of light strikes a plate of glass at right angles to its surface, it moves more slowly through the glass, but passes out on the other side unchanged and in the same direction, both sides of the beam, so to speak, being equally retarded by the glass plate. But if it strikes the plate at an angle, one side of the wave-front will strike the plate before the other and be retarded, while the other, moving at the original

rate, will swing round and thus the direction of the whole beam will be altered. Similarly, after passing through the glass, one side of the beam will come out first, and, being now in a less dense medium, will move more rapidly, while the other side, which has not yet come out of the glass, is still moving more slowly, and so the beam suffers another swing, bringing the whole back to the original direction but on another parallel. When the ray is passing through a lens the same thing takes place, but the new direction will not be the same as the original one. In a biconvex lens the rays will be bent twice in the same direction, and consequently will converge or come to a focus, while in a biconcave lens they will be bent twice in opposite directions and so be dispersed.

About this time a Danish doctor, called Bartolinus, obtained from Iceland a mineral which he called "Iceland Spar," a substance known to chemists as calcite. The crystals of this mineral are in the form of rhombohedra (Fig. 53), and on examining one of them he noticed that it behaved in a very peculiar manner with regard to light, for he found that when he looked at a small object through the crystal it appeared double. Huygens came across Bartolinus's account of this curious phenomenon and proceeded to investigate it, and gave his results in his "Treatise on Light," published in 1690. In all other transparent bodies known to him there is one simple refraction, but in Iceland Spar there are two. In ordinary cases, when a ray falls perpendicularly on a transparent surface, it passes through the body without any refraction, but if it falls obliquely it is refracted. In Iceland Spar, however, the perpendicular rays are refracted and the oblique rays pass straight through It appeared to Huygens, therefore, that the crystal was more "elastic" in one direction than in the other. He further discovered that if the two rays were made to pass through a second crystal they remained separate and did not change their direction. He next found that if he turned the second crystal slightly round on its axis each of the two rays was

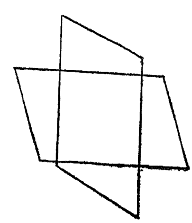

FIG. 53.—CROSSED CRYSTALS OF ICELAND SPAR.

again split into two, so that he got four rays of varying brightness. When the second crystal was at right angles to the first—*i.e.*, had been turned round 90° (Fig. 53)—the two rays reappeared, but had changed their characters, for the one that had behaved normally now behaved abnormally and vice versa. Huygens confessed himself unable to explain this curious result, and it remained unexplained for over 100 years, until further discoveries led to the study of a new chapter in optics called "polarised light." That we shall come to in due course.

We are now approaching the nineteenth century, during which, perhaps, more great discoveries were made and more remarkable men lived than in any other century of our era. Our chief difficulty will be to decide what and whom to include and what and whom to omit, for to treat of all would be impossible. But there is another difficulty that faces us, and that is, how far may we follow a purely scientific discovery into its practical applications? Take two examples to illustrate this point. A discovery of great importance in pure physics was made by Professor Joseph Black of Edinburgh University, towards the end of the eighteenth century, and had it not been for that discovery James Watt could never have been able to improve (for he did not "invent") the steam engine in such a way as to make it what the Americans would call "a paying concern." Then, again, another great man, Michael Faraday, induced an electric current in a coil of wire by thrusting into it a powerful magnet, and this coil and magnet was the forerunner of the modern dynamo. The practical applications of what are apparently very simple scientific discoveries are so numerous that, were we to discuss a tithe of them, this little book would rapidly expand into a library. We must therefore content ourselves with mentioning only a very few.

Perhaps the best way of gaining a knowledge of the advances made in physics during the later years of the eighteenth and the earlier years of the nineteenth centuries is to consider the chief departments of the science separately—sound, light, heat and electricity—and as it does not much matter which of these we take first, we may begin with sound.

Sound

What is sound? If a tuning-fork be pinched and the prongs released smartly, one hears a musical note, and if the tips of the prongs be watched closely, they will be seen to be vibrating. The vibrations set up waves in the air which beat against the drum of the ear and give us the mental impression of a musical note, let us say C, on the pianoforte. If we pinch the prongs gently the note sounded may be so feeble that we must put the fork close to our ear in order to hear it; if we pinch them strongly, or, better still, place the tip of the handle on the lid of an empty box, the sound is much louder but of the same "pitch," as it is called. The pitch is determined by the number of vibrations of the prongs per second and the number is the same whether the sound be faint or loud. The loudness depends on the range of the air-waves from the fork to the ear, known as the "amplitude"; the greater the amplitude the louder the sound, but the pitch remains the same. Some tuning-forks are provided with sliding bars (Fig. 54) which can be set to marks on the prongs corresponding to the different notes of the scale. If the bars be moved from C to D, let us say, the pitch will be a full tone higher; by so doing we have altered the "frequency" of the vibrations, and the higher the frequency the higher the pitch.

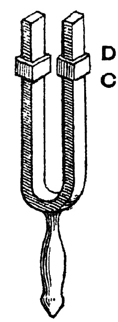

FIG. 54.—TUNING-FORK WITH SLIDE.

The pianoforte keyboard is divided into octaves, or spans of eight notes, and between any two of these notes there is a musical "interval," which depends on the frequency of the vibrations of the two successive wires struck when the corresponding keys are touched. This difference in frequency is called the "ratio." Thus if one note has a frequency of 1,000 vibrations per second, and another a frequency of 500, the ratio is $\frac{2}{1}$, meaning that the first wire is vibrating twice as fast as the second (octave). So long as the ratio is the same, it does not matter where one begins to play a scale. A singer may be

accompanied on any "key," or, in other words, the accompaniment may be "transposed" to suit the range of the singer's voice. As many players are not sufficiently expert pianists to transpose an accompaniment at sight, songs are often printed in two or more keys to suit the performer. In the pianoforte we have a succession of musical scales, and if we call the ratio of the first note of the octave $\frac{1}{1}$, the next will be $\frac{9}{8}$, then $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$ and $\frac{2}{1}$, so that the eighth note above that from which we started has twice the frequency of the note an octave below. In actual practice half tones are introduced between C and D, D and E, F and G, G and A, A and B, represented by the black keys, so that the scale on the piano really includes thirteen notes.

When two or more notes are sounded at the same time they may be in "accord" or in "discord" to our ear, and when a pianoforte is "out of tune," it means that the frequencies are not in their proper ratios. Again, when a note is struck on an instrument, it is very rarely pure; there are almost always what are called "overtones," or vibrations of greater frequency (octaves and higher), and these overtones, so long as they are in harmony with the base-note, give the special "timbre" or quality to the instrument.

Sounds of irregular frequency, like, say, the tapping of a hammer, do not impress us as musical notes at all, but merely as noise. The lower limit of a distinctly musical note is about thirty vibrations per second and the highest about 35,000; anything higher than that is, as a rule, quite inaudible. Few people can distinguish notes of above 25,000 vibrations per second, and as a person's age increases the ear drums usually become less sensitive, and the power of appreciating sounds, and especially high ones, becomes less and less.

In early days several investigators paid attention to this subject, and prominent among them was Joseph Sauveur, who was born in 1653 and died in 1716. Most of his experiments were made on air waves within organ pipes, and his results are all the more remarkable since his speech and hearing had been very imperfect from early boyhood. The conclusions he came to were, however, fully confirmed by a great physicist

of the nineteenth century, called Helmholtz, who was also distinguished by other discoveries in the science of physics.

The subject of "acoustics," as it is sometimes called, was studied afresh by Ernst Chladni, who was born in Saxony in 1756. Chladni, like so many other young scientists, was trained for a profession—law—for which he had no taste, but which was forced on him by his parents. After his father's death he began to devote himself to music, of which he was passionately fond, and, on finding that so little had been written on the physical aspect of sound, he determined to discover if possible some of the laws of harmony. He was acquainted with the curious figures that appear on sheets of glass when sprinkled over with powders of various kinds and exposed to the action of magnets, and this gave him the idea of trying to produce similar effects by striking or rubbing plates of metal treated in the same way. He fastened a thin sheet of brass, B, in a vice, V (Fig. 55, A) and rubbed the edge of the sheet with a violin bow. The result was a musical note due to the vibration of the plate, and this was accompanied by the arrangement of the grains of powder in the form of a star or other pattern (B), the number of rays being dependent on the number of points where the vibrations of the plate were "damped" or stopped by placing the fingers on the margin of the disc. He obtained some very remarkable results in this way, according to the shape of the plate, the place where the violin bow was applied, and the number of points where the vibrations were damped. "Chladni's figures" formed the subject of mathematical investigations during the nineteenth century, but into a discussion of these we need not enter.

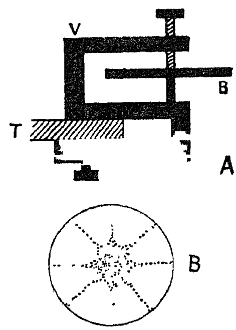

FIG. 55.—A, CHLADNI'S APPARATUS; B, ONE OF HIS FIGURES.

Light

At the end of the seventeenth century, it will be remembered, there were two theories as to the transmission of light, both of which had their supporters—viz., Newton's "corpuscular theory" and Huygens's "undulatory theory." Newton's great name and reputation led most people to adopt his view of the phenomenon, but, on the other hand, Huygens's theory, although it postulated the existence of a universal medium pervading all space, an "ether" which could not be seen, felt, weighed or in any other way identified, seemed to have much in its favour.

Thomas Young, to whom we have already referred, was a most versatile person. He was not only an excellent linguist, for it is said he could speak seven languages, but he was also an authority on hieroglyphics, a subject which engaged the attention of Newton in the later years of his life. In his own profession of medicine he showed how the curvature of the crystalline lens of the eye was unconsciously altered to accommodate it for vision of objects at varying distances. In relation to colour he held that there were only three primaries, red, green and violet (Fig. 56), and that all other colours were due to the mingling of these in different proportions. He also asserted that there were three sets of nerve endings in the retina which received these sensations and conveyed them by the optic nerve to the brain. This view received considerable support long afterwards when the pathological condition known as colour blindness came to be investigated.

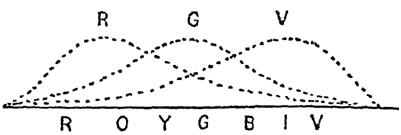

FIG. 56.—PRIMARY COLOURS ACCORDING TO YOUNG.

The Doctrine of Interference—YOUNG.—It was only to be expected that Young should be led to study the subject of optics in general, and to attempt to settle the question whether Newton's views or those of Huygens were correct. His contribution to the discussion was his exposition of the "doctrine of interference." A simple illustration will make this subject clear.

Consider two sets of water-waves meeting each other and passing into a narrow canal (Fig. 57). Two possibilities then arise. When the two sets of waves reach the mouth of the canal the crests of one set may coincide with the crests of the other (B), and the hollows between the successive crests may also coincide; on the other hand, the crests of one set of waves may coincide with the hollows of the other set (A). In the former case the crests unite, and the wave passing into and along the canal will be larger than either of the two waves that combine to make it. In the latter case the crests of one set of waves will fill up or neutralize the hollows in the other set, and an approximately level and calm water ensues along the canal.

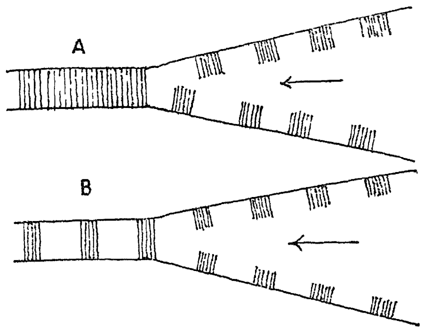

FIG. 57.—INTERFERENCE OF WAVES.

Working on such a basis, Young proceeded to study waves of light, on the assumption that the undulatory theory was the correct one. If a ray of light of uniform wave-length be allowed to enter a dark room through two minute apertures placed close together, the two rays will interfere with each other, and if a screen be placed some little distance from the apertures, the result will be a number of bright bands separated by dark ones. The central bright band, all parts of which are at the same distance from the aperture, is formed by the union of two waves of light whose crests and hollows are combined, crest on crest and hollow on hollow, as in B in our example of water waves (Fig. 57). The same is true of the bright bands on either side of the central one. What of the black bands between them ? In the middle of these the light waves meet each other, crest to hollow and hollow to crest; they neutralise each other, and the result is darkness. When we use ordinary sunlight for our experiment, we find it impossible to obtain absolutely black intermediate bands, because the sunlight is made up of rays of different wave lengths. Hence if the red

rays interfere with each other the blue ones may not; on the contrary, they may even intensify each other, and that is why we always find pale-coloured bands when the light is not pure or of uniform wave-length (monochromatic).

Polarised Light.—The problem of the strange behaviour of crystals of Iceland Spar in relation to light (p. 109) was reopened by an accidental discovery made by the French engineer, Malus. On one occasion he was examining, through a crystal of Iceland Spar, light reflected from a window opposite his lodging, and noticed that, when he held the crystal in a certain way, he saw not two images but one. On changing the position of the crystal the double image appeared, but one of the images was brighter than the other; on turning the crystal a little further, he got once more only a single image. He next discovered that it was only when the reflected light came at a certain angle that the crystal behaved in this remarkable manner, and that the angle differed according to the nature of the substance from which the light was reflected. Light that behaved in this way he called "polarised light."

The subject was at once taken up by Young, and also by a Frenchman named Fresnel who was born in 1788 and died in 1827. He spent his short life in retirement in Normandy, for, being a royalist, he was not in favour with Napoleon and his government. Fresnel was an intimate friend of Young, and when the problem of polarisation was reopened by Malus, both these investigators made efforts to explain the phenomenon. The explanation they arrived at was, very roughly, as follows:

Waves of ether like water-waves travel at right angles to the plane of oscillation. Take a compass card and join opposite points, N-S, W-E, and any other opposites in between, and then pierce the centre of the card with a needle which will indicate the path of the ray, the plane of the card being kept vertical to the needle. The waves of light will always be in the plane of the compass card from any one point to the opposite one. Crystals, however, have the peculiarity of permitting waves to pass along two pathways only, and these pathways are at right angles to each other—*i.e.*, if the one path be N-S, the other is W-E. Hence a crystal splits a beam of light into two

beams which travel at different rates, and are therefore refracted unequally. Each beam is called a beam of "plane polarised light." Different crystals behave in different ways in relation to the rays of light. Thus tourmalin, a very beautiful mineral, first obtained from Tourmali in Ceylon, absorbs one of the two rays, and hence the light passing through it is "plane polarised." If two crystals of tourmalin be superposed, A (Fig. 58), they allow only one beam to pass through, but if one of the crystals be turned through an angle of 90° so that they cross each other at right angles (C), the ray that passed through the first crystal is "interfered" with, and blocked by, the second crystal. It is on this principle that the instrument known as the polariscope is constructed.

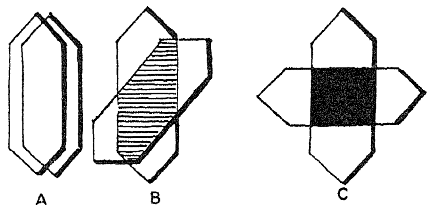

FIG. 58.—POLARISATION OF LIGHT WITH CRYSTALS OF TOURMALIN.

Heat

In the early years of the eighteenth century, and, indeed, for long afterwards, heat was believed to be a substance which, later, received the name of "caloric." It was regarded as "an extremely refined fluid that was able to force its way between the ultimate particles of the densest bodies." This conception of the nature of heat was almost universally accepted until the very end of the century. It seems strange to us that scientific men even in those early days did not realise that since a hot body was no heavier than the same body when cold, heat could have no weight, and that since weight was a property of matter, heat could not be matter.

In the year 1728 there was born, at Bordeaux, a boy called Joseph Black, whose father was a Scotchman carrying on the business of a wine merchant there, and also in Belfast. Joseph was educated first at Belfast and afterwards at Glasgow University, where, in time to come, he became professor of

medicine and chemistry, ultimately removing to Edinburgh to hold a corresponding position there. It was in Edinburgh that Black made the acquaintance of Hutton, the author of the "Theory of the Earth." What Black did for chemistry will be discussed later on; here we are concerned only with his discoveries in physics.

Heat and Temperature—BLACK.—In order to understand what these discoveries really were, it may be as well to glance at certain general facts, of which we have all had experience.

What exactly do we mean when we say that such and such a thing is hot or cold? Our own bodies have a certain temperature which never changes appreciably; it is always about 98·5° of the Fahrenheit scale. In the warmest regions of the earth, where the outside temperature may be far above 100° F., the temperature of the body does not rise over 1° from the normal, and in such terrible districts as Northern Siberia, where a temperature of −88° F. has been recorded, still the body temperature seldom sinks below 98° F. Should the doctor's thermometer reach 103° F., we are regarded as "feverish"; our condition becomes grave if it reaches 105° F., and anything above that, if long continued, is generally fatal. Our body, therefore, gives us a standard to go by, and when we say it is "very hot" on a blazing July day, or "very cold" in mid-winter, we are comparing the climate with our own almost constant temperature.

But further consideration of the facts leads us to the belief that the human body is, after all, not a very reliable judge. A very well known and often quoted experiment soon convinces us that heat and cold are not quite so easily defined as might at first sight be imagined. Obtain three vessels and fill one with very hot water, the second with ice-cold water, and the third with tepid water. Place the right hand into the hot water and the left into the cold, and after a few moments, transfer both hands to the tepid water. The right hand will tell us that the third vessel contains cold water and the left hand will say it is hot! Which hand is to be believed, for obviously the water in the third tumbler cannot be hot and cold at the same time?

Take another simple experience. Put half a pint of cold water into a chemical beaker—a tumbler made of fire-resisting glass—and place it over a spirit lamp for, say, a quarter of an hour. The water by that time will be hot, if not boiling. Put ten half-pints of cold water in a copper kettle, and place that over the spirit lamp for the same time. At the end of a quarter of an hour the water will be barely warm. Yet the beaker with its half-pint and the kettle with its ten half-pints have both received the same amount of heat. Heat and temperature are thus two different things; two bodies may contain the same amount of heat and yet be at very different temperatures.

Again, suppose we place a block of ice in a pan on a hot stove; of course, as we might expect, the ice will begin to melt. Stir the ice about in the pan so as to mix the resulting water thoroughly, and it will be found that, so long as any ice is left unmelted, the temperature of the water remains that of ice—viz., 0° C. or 32° F. What has become of the heat? Keep on heating the pan; now, when the ice has disappeared entirely, the water will get hotter and hotter until the thermometer tells us that the temperature is 100° C. or 212° F. So long as the air pressure remains constant, and no matter how much we may raise the temperature of the stove or how long we may continue the heating, the temperature of the water never rises above the boiling-point mark. Again, what has become of the heat?

Black's Theory of Latent Heat.—Keeping these simple facts in mind, let us turn to Black's enquiries into the nature of heat, the "subtle fluid," as it was called in his day. Black's experiment was very like that we have just made. He filled two flasks, one with ice-cold water and the other with an equal weight of actual ice, and left them in a room whose temperature was kept at 8·5° C. or 47·3° F. In half an hour the water, which at the start had registered 0° C., had risen to 4° C. (It is easy to turn the centigrade scale into the Fahrenheit by remembering the following rule: double the centigrade figure, subtract a tenth and add 32. Thus $8{\cdot}5 \times 2 = 17$; $17 - 1{\cdot}7 = 15{\cdot}3$; $15{\cdot}3 + 32 = 47{\cdot}3$.) The ice in the other flask was melting, but the temperature of the mixture of ice and water was still 0° C. Ten and a half hours later all the ice had melted,

and the resulting water had risen from 0° C. to 4° C., a temperature that the other flask had reached ten hours previously. During all that time the flask with ice in it had been absorbing heat, and if half an hour was sufficient to raise the temperature of the ice-cold water 4° C., then in the twenty-one half-hours the other flask must have absorbed heat equivalent to raising its temperature 21×4 or 84°, while, in reality, it had raised it only 4° C. The obvious conclusion was that all the heat equivalent to 80° had been spent in turning the ice into water without raising its temperature at all.

In another experiment Black discovered that if he mixed a pound of ice-cold water with a pound of water having a temperature of 79° C., the temperature of the resulting mixture was 39·5°, but that when he melted a pound of ice by means of a pound of water at 79° C., the temperature of the water when all the ice had melted was 0° C. The whole of the heat represented by the 79° of the hot water had thus become hidden or "latent" in the 2 pounds of water, and there was nothing to show for it. It was by experiments such as these that Black was able to formulate the two important conceptions, which we are familiar with as specific heat and latent heat.

COUNT RUMFORD.—The next step forward was taken by Benjamin Thompson, better known as Count Rumford. This man had a rather adventurous history, and, as this is rarely given in books on physics, we may, perhaps, spend a moment or two on it.

He was born in the State of Massachusetts in 1753, and began life as a schoolmaster; but, holding royalist views, he had to leave America, and became an official of the Colonial Office in London. He had always been a keen student of the experimental sciences, and for his work on explosives he was elected a Fellow of the Royal Society. After a short period of soldiering in America, he returned once more to England and was knighted for his military exploits. On the conclusion of the war he migrated to Bavaria, where he entered the service of the Elector, and soon rose to high rank. He proved himself to be a man of prodigious energy and great ingenuity. He reorganised the Bavarian army and established military schools

and gun factories, and used his knowledge of engineering in draining marshes near the large cities. Seeing that Bavaria swarmed with beggars, he introduced a poor law system, based on the principle "work for the state and the state will house, clothe and feed you, but not unless." He also took in hand the training of the common people in cookery, invented various kinds of nourishing and palatable dishes, and all sorts of cooking apparatus to render the manner of living more economical. He also turned his attention to agriculture, encouraging the cultivation of the potato as an article of food, and suggesting methods of improving the breeds of horses and cattle. All these and other highly important labours brought him honours both public and academic, and amongst other distinctions he was created a Count. He then took the name of "Rumford," after the original capital of the State of New Hampshire.

Foundation of the Royal Institution.—During a visit to England he founded, at his own expense, what we know as the Royal Institution, where lectures and other courses of instruction might be given—in the words of its prospectus—"for diffusing knowledge and facilitating the introduction of useful mechanical inventions and improvements, and for teaching the application of science to the common purposes of life." As this institution became the scene of the epoch-making discoveries of men like Davy and Faraday, it may be realised what Rumford accomplished for the benefit of science and of the nation. To this day our most distinguished men of science are only too proud to be elected to professorships in the Royal Institution.

Having retired from the service of the Elector of Bavaria, he married the widow of the great chemist Lavoisier and settled near Paris, where he died in 1814.

Heat a Mode of Motion.—It was during his work in connection with his gun-factories that he made his most important discovery on the nature of heat. One day, while watching the boring of cannon in his foundry, Rumford noticed that the metal shavings and the gun itself were far too hot to touch, and very naturally argued that heat could not be a substance, however "subtle," if it could originate merely by rubbing two bodies

together. Even when he caused the guns to be bored under water heat was produced, for the water in which the boring took place became quite hot. He then carried out some experiments by causing a heavy steel drill to revolve rapidly in a hollowed-out block of brass, after filling the cavity with water. After a couple of hours the water was boiling, the heat being produced by the friction of the steel against the brass. His conclusion was that heat is not a substance but a "kind of motion."

Almost immediately afterwards the English chemist, Humphry Davy, who, at Rumford's invitation, became professor at the Royal Institution, obtained sufficient heat to melt two blocks of ice by simply rubbing them together. The heat obviously could not have come from the ice, seeing that ice could not be above 0° C. (freezing-point), nor could it have come from the air, for the experiment succeeded equally well when it was performed in the vacuum of an air-pump. So heat, as Davy expressed it, is "a peculiar motion, probably a vibration of corpuscles of bodies, tending to separate them." The old name "caloric" thereafter disappeared from science as a name for heat, although we still use a word like it—"calorie"—to signify a unit of heat-quantity.

The change of matter from one state into another as the result of heating it, as, for instance, the transformation of ice into water or water into steam, simply means that the particles, when their temperature is raised, jostle each other more and more vigorously, until they escape from each other's attractive influence, especially in the condition of steam or water vapour, while conversely they are more and more crowded, or move less and less actively when they assume the solid state. There must come a time, therefore, when the jostling ceases altogether, and that temperature, which has been very nearly reached artificially, is called the "absolute zero," for if there be no motion among the particles there can be no heat. This absolute zero has been estimated at −273° C. On the other hand, we cannot fix any maximum temperature limit, though there are some very high temperatures that have been ascertained that may be of interest to mention.

When we speak of a poker being "red hot," its temperature is about 500° C., the temperature at which coal burns. When the poker is at a "white heat," it is over 1,000° C. The electric carbon arc gives a temperature of 3,500° C., and the surface of the sun is estimated at 6,000° C. Astronomers, or rather astro-physicists, tell us that the temperature of the centre of the sun is something like 40,000,000° C.! At the other end of the scale, the freezing-point of mercury is −39° C., or, on the Fahrenheit scale, over 70° of frost, and the freezing or solidifying point of the gas hydrogen is −258° C.

We said at the beginning of this section that we might select for consideration one or two of the best-known inventions that arose out of the discovery of natural laws, and that of latent heat, due to Joseph Black, gives us an opportunity of redeeming our promise, for on this law rests the principle of the steam engine. Ask a friend who it was that invented the steam engine, and the chances are that, in nine cases out of ten, the answer will be James Watt, and he will probably repeat the old tale about Watt having got the idea from watching the steam escaping in puffs from the lid of a kettle boiling on the hob of his mother's kitchen fireplace. That story has, probably, as much truth (or as little) in it as there is in that of King Alfred's burnt cakes, or in the tale of Newton's discovery of the law of universal gravitation by meditating on the fall of an apple in the orchard at Woolsthorpe.

James Watt.—James Watt was born at Greenock on the Clyde in 1736, the son of a small tradesman in poor circumstances, who had lost all his money in some speculation. James elected to become an instrument maker, and went up to London to serve an apprenticeship in that trade. On his return to Glasgow the local trades union would not allow him to open a shop, but the university authorities, hearing of his skill in mechanics, allotted him a workshop within their own boundaries, where Watt undertook repairs to apparatus used in the laboratories, and made himself generally useful to the various professors who required his assistance.

Newcomen's Engine.—One day the professor of physics brought him a model engine that required mending, and it was

while engaged on this piece of apparatus that he began to study the theory of steam engines in general. During the time that Watt was mechanic to Glasgow University, Joseph Black was professor of chemistry there, and he often wandered into Watt's workshop to talk over scientific problems. The two young men—for they were almost of an age—became fast friends. Black was at that time engaged on his researches on latent heat, and to him Watt propounded his views on the chief defects he thought he had discovered in the model he was repairing. The model was that of an engine for pumping water out of mines, invented by Newcomen, who was a blacksmith in Dartmouth in the early years of the eighteenth century. It is essential to master the main points in its construction if we are to grasp the nature of the improvements Watt made on it, but it is unnecessary to go into any detail either of Newcomen's engine or of Watt's modification of it. The figures are therefore just sufficiently detailed to illustrate the principles on which the two machines were built.

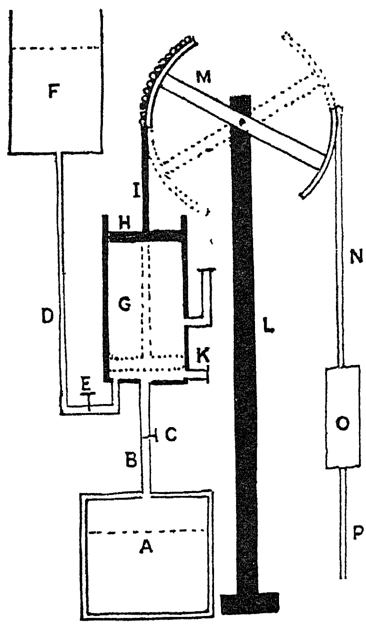

FIG. 59.—NEWCOMEN'S ENGINE.

In Newcomen's engine (Fig. 59) the cylinder, G, stands under one end of a beam, M, pivoted on a rigid support, L. The cylinder is open at the top; steam from the boiler, A, enters the base of the cylinder by a tube, B, on the course of which there is a tap, C. When the steam enters the cylinder it first drives the air out by the outlet, J, which is provided with a valve opening outwards only. The piston and rod, H, I, rise, and the beam swings into the position seen in the figure, being pulled up by the counterpoise, O, at the end of the rod,

N, which in turn passes to the pump, P, in the mine below. The tap, C, is now closed, the cylinder at this moment being full of steam, but at low pressure. The cylinder is also connected with a tank of cold water, F, by way of the tube, D, which has on its course the tap, E. When E is opened cold water flows into the cylinder, causing the steam to condense into water and therefore tending to produce a vacuum in the cylinder. The atmosphere now presses the piston down to the position shown by the dotted lines, thus pulling up the rod, N, and its continuation, P, in connection with the pump. When the piston reaches the bottom of the cylinder the tap, E, is shut and C opened, and the whole performance is repeated. Of course, the alternate opening and closing of the taps, C, and E, is carried out automatically by connecting them with the swinging beam.

The apparatus is obviously an exceedingly clumsy one, calling for improvements in many ways, but there was one item in its construction that Watt rightly regarded as a fatal flaw—*i.e.*, the great waste of heat and consequently of fuel. At every stroke of the piston the entry of the cold water from the tank, F, cooled down the cylinder and piston, so that these had to be reheated every time the piston rose, using up a large amount of heat that might be better employed.

Watt's Steam Engine.—Watt then consulted his friend Black and learnt of his doctrine of latent heat, and realised that steam contained heat stored up in it, or latent, which had to be extracted from it before it once more became water. This, in Newcomen's engine, was done inside the cylinder, so cooling it, and one evening, it is said, while walking in Glasgow Green, the idea occurred to him: " If I can condense the steam elsewhere, the cylinder will remain hot, and all this fuel will be saved." Fig. 60 shows how he successfully solved the problem.

C is the cylinder, now closed at the top, in which the piston, K, moves up and down. The cylinder is pierced at either end by two tubes in pairs, E, F and G, H. E and H are connected to a tube from the boiler, M (not shown), and F and G to another tube which connects with the condenser, A. The condenser has an outlet pipe, L, and is sur-

rounded by another cylinder, B, which has an inflow pipe, I, from a tank of cold water (not shown), and another outflow pipe, J. The pipes, E, F, G, H, have valves so arranged that when E and G are open, as in the figure, F and H are closed, and *vice versa*. The piston-rod, D, may be connected with a pump, a fly-wheel, or the driving wheels of a locomotive, or, indeed, with any machine in which it is desired to produce "motion against resistance," or, in other words, to perform work, so that we need not represent beams or other apparatus beyond letter D.

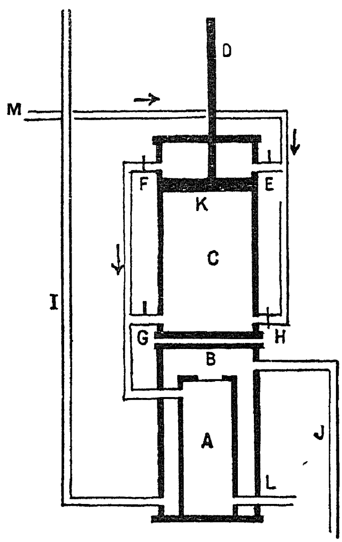

FIG. 60.—WATT'S STEAM ENGINE.

How does the engine work? Steam comes along the tube M, from a boiler, when, let us say, the valves E and G are open and F and H are closed, and, being under pressure, forces the piston down to the bottom of the cylinder. Then automatically, by means of connecting-rods, not shown in the figure, the valves F and H are opened and E and G are closed. The steam now enters by H, below the piston, and drives it up, the old steam escaping by the valve, F. From F it passes to the condenser, A, enclosed in the jacket cylinder, B, filled with cold water from the tube, I, leading from the cold-water tank. In A the steam is condensed by the cold jacket and escapes as water by the outlet, L. Meanwhile the water in the jacket, continuously warmed by the steam in the condenser, flows out by the tube, J, and is continually renewed from the tank, ready to cool the flow of steam driven intermittently into the condenser.

It will be seen that Watt's invention was an apparatus for condensing the steam apart from the working cylinder, so that the latter always remained at or about steam temperature. As a consequence, all the heat that in Newcomen's engine went to

warm the cylinder after the condensation of the steam within it was now available for doing mechanical work. Another improvement was that steam was made to push the piston down as well as up, helped by the vacuum in A, and air pressure avoided. Newcomen's engine might be described as a half-steam, half-air pressure engine, and Watt's as a whole steam-pressure engine.

Conservation and Dissipation of Energy.—A new problem had now to be faced by the physicists which was the outcome of the work done by Rumford and Black. Their experiments had shown that mere mechanical labour could be turned into heat. Work means expenditure of energy or, conversely, energy is the power to do work. Anyone who works extremely hard is said to be "very energetic," and it does not matter what the nature of the work is. It may be actual visible labour, such as running up a hill or pulling an oar, or invisible work, such as composing an essay or solving a problem in geometry. Even when one is asleep the heart is beating, the alimentary canal is digesting, the brain is receiving and sending messages from and to muscles and glands. All this is work, visible and invisible, and its performance requires the expenditure of energy.

Any kind of body possesses energy if, by its means, work may be done. The energy may be hidden in it, ready to be called forth under certain conditions. Thus one's arm at rest contains energy which may be employed in lifting a weight or pulling an oar. The coiled-up spring of a watch contains energy which, when released, causes the wheels to revolve. A milldam full of water possesses energy which, when the sluice is opened, drives the mill wheel. Energy in this quiescent condition is called "potential" energy. When we actually lift the weight or pull the oar, when the watch spring uncoils or the water flows out of the milldam, the potential energy becomes active or "kinetic," from the Greek word meaning "motion," as in the word "kinematograph" or moving picture. Heat being a mode of motion is, therefore, kinetic energy. Coal contains a store of potential energy, because the carbon which is its principal constituent unites under certain conditions with the oxygen of the air yielding kinetic energy, as heat

and light. This heat can transform water into steam, which drives the piston up and down the cylinder of an engine. This mechanical kinetic energy may in turn be employed to drive the electrical machine called a dynamo and so produce electrical energy, which again causes an electric lamp to glow, giving rise to the form of radiant energy we call light.

Every time one form of energy is turned into another it is done at a loss. Thus the whole potential energy of coal is not available for transforming water into steam, nor is the whole expansive power of steam spent in moving the piston. All the mechanical power of the piston does not go to the turning of the dynamo, and all the electrical power of the dynamo is not converted into light. The potential energy of our arm is not entirely expended in pulling the oar, for we ourselves get hot with the exertion, and such heat is certainly not helping to drive the boat through the water. There is, in short, a loss of energy at every step, and the problem for the engineer is to devise a machine that may reduce these successive losses to a minimum—*i.e.*, to invent the most economical engine possible. Every form of energy is, in the long run, reducible to heat; this heat is eventually given off into space, and we cannot catch it again and make use of it. It is not actually lost or destroyed, but simply becomes unavailable by dispersion.

Thermo-dynamics.—Obviously it is important for us to know how to measure energy in order to be able to draw up a debit and credit account, so to speak, to see how much energy we may use and how much we are losing. It would also be useful to know how much there is of it and what becomes of it. This whole subject, a vitally important one to science, is called thermo-dynamics, and with it we link the names of Carnot, Joule, Helmholtz and Thomson (afterwards Lord Kelvin), four of the great physicists of the nineteenth century.

The Ideal Engine—CARNOT.—Sadi Carnot was the son of the noted Revolutionist, Nicholas Carnot, who took so great a part in the organisation of the Republican armies of France during the political disturbance that preceded the rise of Napoleon. Sadi was born in 1796, but died of cholera at the early age of thirty-six. Short as his life was he found time to produce a work on

the "Motive Power of Heat" that is always regarded as the foundation stone of thermo-dynamics.

Carnot set out to find how much mechanical work it was possible to get out of an ideal steam engine—*i.e.*, one in which there was no loss of energy at all. Such an engine does not exist, for were we to supply it with a certain amount of energy, which we shall call x, and get out of it a certain amount of mechanical work, y, and a certain amount of heat, z, and if we could collect z once more and resupply it to the engine to be turned again into mechanical energy, we should come nearer to solving the problem of perpetual motion than did any of the cranks who puzzled their brains over the subject in the sixteenth and seventeenth centuries. In an ordinary railway locomotive by far the greater part of the energy of the fuel is lost, and only a relatively small balance is left to pull the train. The bigger that balance is the more power we get out of the fuel, the lower the cost of running the train, and, incidentally, the cheaper our railway tickets! Perhaps our far-off descendants may devise some method of utilising the wonderful substance, radium, which modern physicists tell us is one of the unstable elements that constantly evolves energy and yet lasts thousands of years.

The Mechanical Equivalent of Heat—JOULE.—Carnot's work was entirely theoretical and mathematical, and so we need not discuss it, but we must notice that he claimed that it was possible not only to change mechanical energy into heat but also heat energy into mechanical. What the value of the one was in terms of the other he did not try to estimate; that was accomplished by Joule.

James Prescott Joule was a brewer, born in Salford in 1818. In his early years he was more or less of an invalid, and spent most of his time at home pondering over scientific problems. One of these problems was that left unsolved by Carnot—the actual value in mechanical work of a unit of heat. This he solved in the following way (Fig. 61). The figure is simplified as much as possible so as to show the general principle only.

A is a cylinder filled with water, in which revolves a series of paddles, B, attached to the axle, D. The cylinder also con-

tains a thermometer, C. The top of the axle passes through a roller, F, which may be fixed to or released from the axle by the pin, E. Round the roller is wound a cord which passes over the drum, H, and on the same axis is another smaller drum, I, also having a cord wound round it, ending in a 1-pound weight, J. By winding up the drum, I, the cord is unwound from the drum, H, and thus the weight, J, is lifted to the top of the scale, K. When J is released, by its fall, in obedience to gravity, it causes the roller, F, and consequently the paddles inside the cylinder, to revolve. When the weight, J, has reached the ground, the pin, E, is released and the roller is rewound without disturbing the water or the paddles. Owing to the beating of the paddles on the water the temperature of the water is raised and the rise is recorded by the thermometer, C, while the scale, K, indicates the number of feet the weight has fallen in a given time. It will be seen, therefore, that the amount of actual work done by the falling weight can be measured in terms of heat.

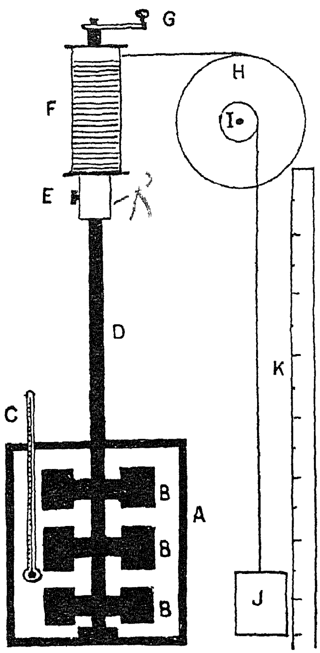

Fig. 61.—Joule's Apparatus for Determining the Mechanical Equivalent of Heat.

After making allowances for friction, cooling of the cylinder, and so on, Joule was able to say how much mechanical energy had to be expended in order to raise the temperature of 1 pound of water 1° F. He found that to do this the weight must fall 722 feet. (The number is now determined as 778 feet.) Conversely, the energy sufficient to raise 1 pound of water 1° F. would lift a 1-pound weight 778 feet. The unit, viz., the work done in lifting 1 pound a foot, is called a "foot-pound."

The First Law of Thermo-Dynamics.—Of course, at every step there is a loss of energy in the form of heat, but these losses

Joule, as we have said, allowed for in making his calculations, given in his paper published in 1843. When stated in general terms we get what is known as the first law of thermo-dynamics —viz., when, during any transformation of one form of energy into another, heat is produced, the amount is always the same for the same amount of energy, whatever its form, and if heat disappears, exactly the same amount of some other kind of energy will appear in its place.

All this work of Joule's and much more that we must pass over led to the discovery of two great generalisations—the laws of conservation and of dissipation of energy. The law of conservation of energy means that the sum total of the energy of the universe is a constant quantity. We cannot destroy energy and we cannot create it, we can only turn it from one form into another. It may be potential or it may be kinetic, but all the potential energy plus all the kinetic energy is a constant quantity. This fundamental law was expounded at great length and very brilliantly, in 1847, by the German physicist, Helmholtz. "We cannot create mechanical force," he says, "but we may help ourselves from the storehouses of Nature. The brook, the wind which drive our mills, the forest, the coal beds which supply our steam engines and warm our rooms, are the bearers to us of the small portion of the great natural supply which we draw upon for our purposes."

The Second Law of Thermo-dynamics.—But there is a second law of thermo-dynamics which was hinted at by Carnot and expressed by Clausius, professor of physics at Bonn, and who was a contemporary of Joule. This law states that the work-efficiency of a reversible engine depends on the temperatures at which it takes in and gives out heat; from which it follows that heat cannot be conveyed from a colder to a warmer body. We can raise the temperature of water in a kettle to 100° C., but we cannot transfer any of that heat to the fire. "Of course, everyone knows that," it may be said, but, a century ago, everyone did not know it, nor did they see where belief in such a law must lead them. When heat is supplied to an engine it is impossible to use it all in the performance of mechanical work, as Watt realised. The heat

that is not used in moving the piston to and fro escapes and warms all the articles round about, which pass on the heat to the air and the walls of the engine-room, and so to the exterior. The heat is thus diffused or dissipated; we can make no use of it, and are quite unable to collect it again in a condensed form for work.

The law of dissipation of energy was explained for the first time by one of our most brilliant physicists, Sir William Thomson (afterwards Lord Kelvin), in 1852. If we regard our earth as a gigantic clock, kept going by its stores of energy, and if these stores are constantly being degraded into the form of generally diffused heat, then, in time, the clock must run down. It certainly is running down, but, even if it received no new supplies, the internal heat will last many millions of years yet. On the other hand, its surface is constantly receiving new supplies from the sun, and these supplies, as we shall find by and by, are, in part, being stored up by plants in the form of wood and other organic materials, to be used as fuel or to maintain life. Rivers flow down to a uniform level—the ocean—and thus are losing all the potential energy they temporarily acquire when they gather into lakes, and all the kinetic energy they release when they are actually in motion. But at the same time the sun is constantly causing evaporation of the surface waters everywhere, and the vapour so produced condenses into clouds which, when they precipitate rain or snow over the land, keep the rivers flowing and the lakes at a fairly uniform level, and so maintain the supply of energy.

It would therefore appear that we are, in the long run, directly or indirectly, entirely dependent for all our supplies of energy on the sun. The sun is a great fiery ball of enormous size, about a million times the volume of our earth, with a surface temperature of about 6,000° C. and an internal temperature of something like 40,000,000° C. But Sol himself is losing energy at a stupendous rate, as we shall see when we study the marvellous advances in astrophysics during the present century. We are thus forced to the conclusion that, unless there be something to compensate for all this loss, the whole universe is drifting slowly, though very slowly, into a cold state. But now we are

getting out of our depth, and had better return to the natural phenomena taking place around us and the laws we can deduce from their observation, and leave these vaster problems to philosophers who devote themselves to what the Greeks called *meta ta phusica*, the things that come after physics, or metaphysics (see pp. 454, 455).

Electricity

We must now turn to the subject of electricity, in which such gigantic advances have been made in our own times. First of all, we must see what progress was made after Gilbert showed his magnetic machines to Queen Elizabeth, and Guericke spun his sulphur ball before the Emperor Ferdinand.

Conductors and Non-conductors—GRAY.—One of the earliest of these pioneers, born about a century after Gilbert, was Stephen Gray, a master at Charterhouse School. This inquisitive person's experiments are not only interesting in themselves but so suggestive of what was to follow, that some account must be given of them. Gray knew all about Gilbert's work and proceeded to extend it. He found that if he rubbed a long glass tube, it, like amber, attracted pith balls and scraps of paper, and that even when he covered the end of it with cork, the "vertue" was passed on to the cork. He then used a fishing-rod, to the tip of which he attached an ivory ball, and found that the ball behaved just like the glass tube. These wonders he showed to a friend, who suggested using a wire supported at intervals by some silk threads from the roof of a long gallery, passing the wire backwards and forwards until it was over 300 feet in length. Still the "vertue" passed from the rubbed rod, from end to end of the line. In one of these experiments the silk threads broke under the weight, so they substituted metal wires as suspenders, but, no matter how much they rubbed the glass at one end, the "vertue" never reached the ball at the other. What was the matter? Why did not the "vertue" travel as before? Suddenly it flashed on them that perhaps the reason was that they had used silk and not wire in their previous experiments. So thicker and stronger silk supports were employed, and the length of their line was increased to 650 feet. Then the "vertue" passed from end

to end of the line quite easily. Here, though Gray did not know it, was the germ of the electric telegraph. Gray was greatly excited over this discovery, and leaving, as he says, his friend to electrify "a hot poker, a live chicken, a large map, and an umbrella," he rushed back to Charterhouse and electrified his boys—in more senses than one—by suspending them by silk cords, touching their feet with an electrified tube, and making bits of paper fly against their faces!

A Frenchman, called Charles Dufay, learned of Gray's experiments and repeated them, but in doing so he discovered certain new facts. He found that metals could be electrified also, provided they were held in glass supports, insulated as we would say, so that the "vertue" did not pass away to the ground from them through the body of the holder; and thus he was led to distinguish conductors from non-conductors. But he went further; he showed that while a rubbed glass rod repelled a film of gold leaf, a rubbed piece of amber attracted it, and so he announced that there were two kinds of electricity, one of which he called "vitreous" and the other "resinous," and that two bodies, each charged with either vitreous or resinous electricity, repelled each other, while if one was vitreous and the other resinous they attracted each other. Dufay's two kinds of electricity are what we know as positive and negative.

The Leyden Jar.—About the same time two Dutchmen, Cunæus and Peter Musschenbrock of Leyden, made a discovery of considerable importance which resulted in a piece of apparatus known as a Leyden jar. In its modern form it consists of an open glass cylinder, A, lined inside and outside with tinfoil, B, C (Fig. 62). Within the jar is a rod touching the inside lining and ending in the knob, D. The inside foil is insulated from the outside foil by the glass A, but the outside is in contact with a table on which the apparatus stands, which acts as conductor to the earth. If D be put in contact with a

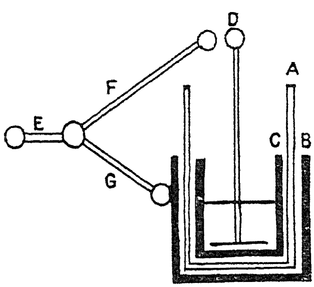

FIG. 62.—LEYDEN JAR.

generator of electricity, the tinfoil C becomes "charged," and if we take a metal fork with two prongs, F and G, united to a glass handle, E, and, while touching the outer tinfoil with G, bring the other prong, F, close to D, we shall get a spark between them, when F and D are sufficiently close together. If the original charge supplied to C is positive, B becomes charged with negative electricity by what is called induction. When a number of these jars are united in series and properly insulated on glass, a well-marked electric shock can be obtained, which, when passed through the human body, used to create great wonderment, not to say fear, among the country yokels at fairs where the travelling conjurer gave his performances.

Lightning Conductors.—The well-known American statesman and scientist, Benjamin Franklin, noticed the spark between the knobs F and D in the Leyden jar, and, in 1749, concluded that a flash of lightning was simply a spark, though on a very much larger scale, between two oppositely charged clouds, and, by means of a kite carrying a wire, he attempted to draw off what he called the "electric fluid" from the cloud. This dangerous experiment was a complete success, and now copper lightning conductors are fixed to every lofty building to guide the destructive charge by the easiest pathway to the earth, where it is lost and becomes harmless.

While Franklin was thus risking his life in drawing lightning from the sky, and in doing so conferring a boon on mankind, two Italians were beginning a new chapter in the history of electricity. These were Luigi Galvani, professor of anatomy in the University of Bologna, and Alessandro Volta, professor of physics in the University of Pavia. Galvani was a man of some note in the science of biology, for he added to our knowledge of the structure of the ear and of the anatomy of birds, but it is to his discoveries in electricity that he really owes his fame. We still speak of a "galvanic battery," just as we commemorate Volta's name in the "voltaic pile" and in the term "volt," meaning a unit of electric pressure or potential.

Animal Electricity—GALVANI.—As is frequently the case in relation to great men of past generations, stories get attached to

their names, like barnacles to an old hulk, but in very many instances these turn out to be mere fables. The story of how Galvani came to make his discovery of "animal electricity" has apparently a germ of truth in it. Signora Galvani, it is said, was preparing a soup from frog's legs, while one of her husband's pupils was turning an electric frictional machine near by. The lad accidentally touched one of the legs with a knife he had in his hand and was startled to see the leg move. The lady informed the professor of this apparent resurrection, and he at once began to investigate the curious phenomenon. He prepared a number of frog's legs to experiment upon, and hung them by copper hooks to an iron balcony. To his surprise, whenever a leg was blown against the balcony, it gave a convulsion, and, since there was no electric machine anywhere near, he came to the conclusion that there was an "electric fluid" in the leg that made itself evident whenever the copper hook was brought in contact with the iron through the frog's leg. The leg was said to be "galvanised into action," a phrase we still use when we speak of spurring on some slow or sleepy worker.

Voltaic Battery—VOLTA.—Volta heard of Galvani's discovery of "animal electricity," as it was called, but, on repeating the experiment, decided that the frog's leg had nothing to do with the electric current, and that the same result could be obtained by using the metals alone without the intervention of the animal. So a controversy arose between the two professors, but before it ended Galvani died, leaving Volta to work out the problem by himself. Long afterwards, with the aid of a delicate instrument, called a "galvanometer" (note Galvani's name in the title), the existence of these electric currents was proved to exist not only in the frog but in all living organisms.

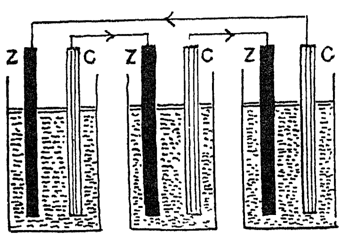

FIG. 63.—VOLTAIC BATTERY.

Volta, being convinced that the electric current was produced by the contact of two metals, proceeded to make what we call a "voltaic battery" by placing strips of copper and

zinc in glass jars containing brine, arranged in series (Fig. 63). When he united the copper strip, C, with the zinc strip, Z, and so through the series, he obtained an electric current whenever he joined the last copper strip with the first zinc one.

Thus by the end of the eighteenth century quite a number of facts about magnetism and electricity had been accumulating, and what now began to exercise people's minds was whether there was any connection between them.

Again and again in the history of science a great discovery is made not by planning out beforehand the end to be gained and then labouring to reach that end, but by mere accident—a lucky shot. In the case of a possible connection between magnetism and electricity, it was pure chance that gave the key and led to the belief that the two sets of phenomena were intimately related to each other.

Electro-magnetic Induction—OERSTED.—In the year 1819 Hans Christian Oersted was professor of physics in the University of Copenhagen, and on one occasion he was experimenting with a galvanic battery in his laboratory. On the table there was also a compass which was pushed by accident close to a bar of copper through which it was intended to send an electric current. It chanced that this bar lay parallel with the compass needle, but naturally Oersted paid no special attention to this detail. When he sent the current through the bar, to his amazement the needle swung round and placed itself at right angles to the direction in which the current was flowing.

Some months afterwards a French physicist, named Arago, gave an account of Oersted's discovery to the Academy of Sciences, and it chanced that among the audience was a man called Ampère, who was born at Lyons in 1775, and who, after a somewhat disturbed youth—for these were the stormy days of the French Revolution, during which his father had been guillotined—became professor in the Polytechnique at Paris. Ampère at once saw the possibilities of Oersted's discovery, and, after a few days' work, was able not only to confirm it but to extend it greatly. He found that when the current in the conductor was flowing from south to north, and the needle of the compass lay below the conductor, the north pole

of the needle swung to the west, but when it lay above the conductor it swung to the east (Fig. 64).

If we place the north pole of one magnetic needle near the same pole of another needle they will repel each other, and the south poles are equally unfriendly, but the north and south poles are attracted to each other. Ampère's experiment showed that the electric current induced magnetic action round it, and from that he argued that two parallel electric wires would act magnetically on each other also. So he placed two rods side by side, both of them free to move, and sent a current through them in both cases in the same direction. The wires at once came together; but when he sent the current in one direction through one wire, and in the opposite direction through the other, they repelled each other. Ampère also measured the strength of the currents, and deduced the amount of attraction or repulsion between them and expressed it in a formula. Thus if two wires are at a certain distance apart, d, and if the strength of one current be c, and if the other c^1, then the force of attraction or repulsion, f, can be measured by multiplying c by c^1 and dividing the product by the distance squared—*i.e.*: $f=\frac{cc^1}{d^2}$.

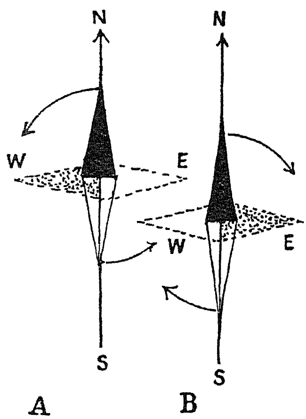

FIG. 64.—AMPÈRE'S EXPERIMENT.

S-N, direction of the current; A, needle below; B, needle above the conductor.

The Galvanometer.—It was hinted above (p. 136) that Galvani's "animal electricity" would be demonstrated later when the galvanometer had come into use, and here we have the germ of the invention. The instruments now employed are constructed on various patterns, but all we need know is the principle on which they work. If a wire be bent into a loop (Fig. 65), and a magnetic needle be placed within the loop, the needle will be under the influence of any current passing through

the wire, and will thus be actuated by two forces, first, its own tendency to point north and south, and, second, the current enticing it to point east and west. The stronger the current the more the needle will vary, and the angle between the needle at rest and after it has been acted upon by the current gives us a figure by which to calculate the strength of the current, and a standard unit of fixed quantity is called an "ampère."

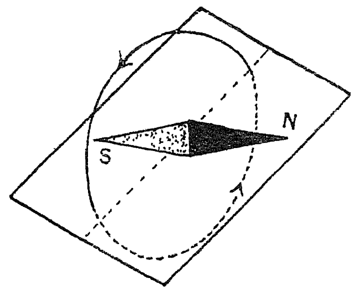

FIG. 65.—GALVANOMETER.

But the idea of surrounding the magnet with a coil of wire led Ampère to something else. He wound a long wire round a bar of steel and sent a current through the wire; the bar retained the magnetic charge and became a magnet, although when he replaced the steel bar with one of soft iron, the latter lost its magnetism the moment the current was cut off. The steel bars were termed "electro-magnets," seeing that they had been made by the use of an electric current.

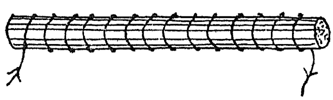

FIG. 66.—ELECTRO-MAGNET.

In 1836 Ampère, who had long suffered from tuberculosis, started on a cruise in the Mediterranean, but before he reached Marseilles he succumbed to his malady, leaving behind him a record of domestic troubles bravely borne, and of scientific achievements which placed him in the front rank of the pioneers of electrical science.

SIR HUMPHRY DAVY.—It has already been noted how men renowned in one branch of science very frequently made their mark in related sciences as well. Black, for instance, though a professor of chemistry, yet established a great physical law—that of latent heat. Sir Humphry Davy, a chemist of no mean order, was also a physicist of first-class rank. He was born in Penzance in 1778, and educated there and afterwards at Truro. Even in his early boyhood he showed signs of genius though of a peculiar sort, not in the least like what

one would expect to find in a future leader in science. Before he was nine years old he recited stories and poems to his schoolmates, entertaining them vastly, no doubt, but hardly helping them in their ordinary tasks.

Davy's father died when he was sixteen, and Mrs. Davy was left with five children, of whom Humphry was the eldest. The widow was at first rather poorly off, and for some years had to help in running a millinery shop, but things improved after she fell heiress to a small estate. Meanwhile Humphry became an apprentice to a Mr. Borlace, a surgeon-apothecary in Penzance, and while studying his profession in the country pharmacy, he spent all his leisure in reading philosophy, history and poetry, writing essays on all sorts of subjects, and even composing verses, which showed considerable merit.

Before he was twenty he began to devote himself to the study of chemistry, and fortunately used as his textbook the famous work that had just come from the pen of the great French chemist Lavoisier. Davy, with Lavoisier's book as his guide, started experimenting on his own account, using the materials and rather crude apparatus in Mr. Borlace's surgery. Some of these "researches," as he rather grandiloquently called them, fell into the hands of a Dr. Beddoes of Bristol, who thought so much of them that he invited Davy to be superintendent of an institute he had founded in that city, the object of which was to study the effects of different gases on the human body. Davy accepted the offer, and entered heartily into the various chemical problems that arose from time to time.

In 1799 Count Rumford had founded the Royal Institution in London. He had just brought out his theory that heat was not a substance but a "mode of motion," and Davy had supported that view by his experiment of melting two blocks of ice by simply rubbing them together. Rumford was naturally impressed, not to say pleased, with this fresh proof of the truth of his thesis, and having heard glowing accounts of Davy's promise from Dr. Beddoes at the Bristol Institute, he invited Davy to come to London and become a member of the staff of the new college. This offer came to him

in 1801, and, with his appointment, began the long and brilliant career that marked him out as the foremost experimenter and teacher of his age.

Guericke's air-pump (p. 47) was by no means a perfect instrument, and Boyle's apparatus (p. 49) was not very much better, but the work that Davy undertook in chemistry, soon after his appointment in the Royal Institution, required a far more perfect "vacuum" than could be obtained by either of these old appliances, so he started to invent an air-pump on a new principle. His idea was that if he replaced the atmospheric air in a bell-jar with another gas, the last traces of which could be removed by chemical means, he might obtain what he desired—a perfect vacuum. He knew that carbon dioxide was greedily absorbed by caustic potash, so he filled the jar with that gas, leaving in it a vessel containing potash. He then pumped out as much of the gas as he could in the ordinary way; what was left over he considered the potash would account for. By this means he obtained a far closer approach to a vacuum than did any of his predecessors.

Count Rumford had seen to it that his new institute was not merely a building with lecture-rooms and laboratories, but that it was also well supplied with appliances wherewith to demonstrate the subjects taught, so that when Davy began his work he found, among a variety of other apparatus, a battery far more powerful than existed anywhere else.

The Electric Arc.—When we were considering the structure of a Leyden jar (Fig. 62) we noted that when the ends of one of the prongs of the fork were brought near the knob of the central rod in contact with the inner tinfoil, a spark appeared between the knob and the prong. Davy studied the sparks given out by the two terminals of the great battery in the Royal Institution, and found that as he drew the ends of the wires apart, not one but many sparks seemed to jump from one terminal to the other, and that both terminals became very hot. After trying many substances, he found that when the terminals were made

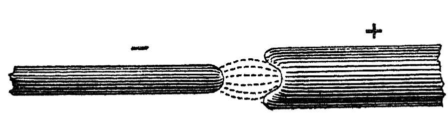

FIG. 67.—ARC BETWEEN CARBON TERMINALS.

of carbon he obtained a brilliant white light, and that the positive pole was worn away by the passage of carbon particles across the gap to the negative pole. When the carbon rods were placed horizontally the flame resembled a bow which he called the "arc," and that the top of the positive pole was hollowed out into a cavity, or crater, the walls of which were at a white heat. He estimated the temperature of this cavity at 3,000° C., and found that he could melt in it many substances, such as quartz or platinum, that were quite proof against the temperature of an ordinary furnace. Thus Davy is responsible for the first beginnings of the electric furnace now found in every well-equipped chemical laboratory, and for the great arc-lamps that illuminate our streets and railway stations.

Electrolysis.—Nearly twenty years previously Cavendish had discovered that when hydrogen and oxygen were mixed in certain proportions in a vessel, and the mixture ignited, the result was the disappearance of the gases and the formation of a dew on the vessel's wall which he found to be water. It so happened that two other physicists, Nicholson and Carlisle, while experimenting with a voltaic battery, found that, when the ends of the two wires were placed in ordinary water, bubbles of gas appeared round each of them, which were hydrogen and oxygen respectively. They also noticed that the water at the positive terminal became acid and at the negative terminal alkaline. These peculiar results they were, however, unable to explain. Davy was very much struck by these facts, and employed his genius to solve the riddle. At first he fancied that the acid and the alkali might have come from the vessel in which the experiment was carried out, so he used, first, agate and then gold cups to hold the water and the terminals, but the acid and alkali still made their appearance. Suspecting that the water he had distilled in the ordinary way might have carried some salts with it, he next used water that had been obtained by natural distillation or evaporation, and found that although the alkali was as prominent as ever, the acid, though still present, was much weaker. Had the air anything to do with it? To answer this question he used his new method of producing a vacuum, and carried out the operation under

the bell-jar of the air-pump. He then found that almost pure oxygen came off at one terminal and almost pure hydrogen at the other, and further that as the gases increased in volume the water in the cup decreased, thus completely confirming Cavendish's discovery of the composition of water.

But this was by no means all. If water could be decomposed by an electric current, he asked himself, why not other substances? The first materials he experimented with were potash and soda, which at that time were considered to be elements. Davy melted some caustic potash in a platinum spoon and connected the spoon with the terminals of his great battery, when, to his amazement, the liquid potash began to bubble, and bright droplets, like globules of mercury, appeared on the surface. He obtained a similar result when he treated caustic soda in the same way. He had obtained from these so-called "elements" two new metals, so that potash and soda must be compounds. The shining globules he christened respectively potassium and sodium. His brother, who was present when this discovery was made, says that Davy was so excited that "he actually bounded about the room in ecstatic delight." And well he might, for he had not only added two new elements to the ever-growing list but he had also discovered a new method of analysis, which was to prove not only of immense value in chemistry but also was destined to be the basis of great industrial undertakings, such as electroplating and electrotyping. The method is now known as "electrolysis," or "releasing by electricity."

Here we may pause for a moment in the story of Davy's discoveries and consider what electrolysis has meant to the silversmith. The handles of forks and spoons and other silver-like articles have certain marks stamped upon them, and one of these is "E.P.," which stands for "electroplate," meaning that the spoon is not solid silver but a far less costly metal—pewter, nickel or some alloy—coated with silver. How is this accomplished? By a method based on Davy's discovery.

Fig. 68 shows how a pewter teaspoon, made from an alloy of tin and lead, may be made to look like silver. A is a bath containing a weak solution of a compound of silver. Supported on

the edges of the bath are two rods, B and C, C being connected with the positive pole of the battery and B with the negative pole. D and E are crossbars, D resting on the positive rods and E on the negative ones. From E depends the spoon to be electroplated, H, dipping into the solution, G, and from D hangs a plate of pure silver, F. The current enters at C, passes along D, and reaches the silver plate, F, and the solution of the silver salt, G. From thence it passes through the spoon, H, and then through the crossbar E to B. So much for the apparatus; next a word as to the method.

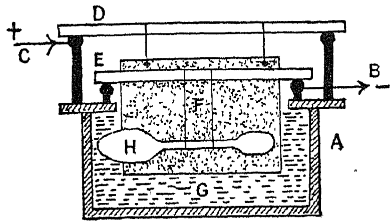

FIG. 68.—ELECTROPLATING.

The spoon is first of all boiled in soda to remove any grease; it is then thoroughly washed and dipped in a solution of nitric acid. Just before placing it in this bath, it is plunged for a moment in a solution of a salt of mercury, which aids the subsequent silvering process. Technically this is called "quickening." The spoon is then suspended by wires from the crossbar E, and the current is turned on. The silver in the solution G in the bath separates out from the salt and is deposited on the spoon, and an equal amount of silver takes its place, dissolving from the plate F, so long as the current is maintained. The time taken in the process depends on the thickness of the silver coating required and the nature of the article to be coated, but usually several hours are needed to lay down a layer of silver as thick as the page of this book. When the coating is completed, the spoon is washed and polished with wire brushes, again washed in boiling water, and dried in hot sawdust.

Electrotyping is another important application of Davy's discovery, without which this book could not have been printed and illustrated, but to describe that process also would be to take up too much of our space. Let us rather return to the Royal Institution laboratory and see what other important work in physics was carried out by its distinguished professor.

Davy's Safety Lamp.—In the early years of last century explosions in coal mines were of very frequent occurrence, and often attended by great loss of life. Naturally this was a matter of the gravest concern to the public, for it made coal-mining a very dangerous occupation, and discouraged men from risking their lives in underground workings in order to supply the fuel needed not only for household fires but also for the furnaces of the great iron and steel trades, and the various other factories then springing up all over the kingdom, wherever coal was to be had most cheaply. To lessen the risk to the miner was also to make him contented with a lower rate of wages, to cheapen coal, and so to benefit both the general public and the manufacturer.

These disastrous explosions that made the miner's life a constant terror are chiefly due to one or other of two causes: the one is what the miner calls "fire damp," and the other is coal dust. "Fire damp" is a gas, often called "marsh gas," because it may be seen bubbling up when a stagnant pool is disturbed. It is a compound, of carbon and hydrogen, also known as methane, and is highly combustible; when it explodes with sufficient air it produces carbon dioxide and water. Carbon monoxide, however, a deadly poisonous gas, frequently appears, as well as carbon dioxide in mine explosions, giving rise to what the miners call "choke damp" or "after damp"—viz., a mixture of carbon monoxide and carbon dioxide. Incidentally it may be noted that the word "damp" is Old German for an exhalation or vapour, not necessarily aqueous. Clearly both these gases deprive the air of the gas, oxygen, which is essential to respiration, while one of them adds a deadly poison to the atmosphere. At the same time the actual explosion may cause great damage to the walls and roofs of the underground passages, so blocking the pathways of escape.

Fine coal dust is also very explosive, as, indeed, are all combustible bodies when in the form of a very fine powder. Obviously miners required lamps to enable them to carry on their work, and yet a bare flame might produce an explosion from either cause, with consequent disaster.

The year 1815 was a particularly bad one for explosions

in the coalfields, and the harassed mine-owners wisely appealed to Davy for help. Davy at once responded, and in a couple of weeks produced his famous "safety lamp," the use of which has saved thousands of lives. The principle on which it is constructed is remarkably simple. Obtain a small piece of fine copper wire gauze and hold it over a gas-jet; turn on the gas and light the jet *below* the gauze. The flame does not pass through the gauze, but rises and falls as the gauze is raised or lowered. Arrange the gauze as before and turn on the gas, but this time apply the match *above* the gauze; now the flame will appear above it, but not below it. The gauze may be raised an inch or two, but no flame "strikes back" to the burner below. The explanation is that the gauze is a good conductor of heat, and the large surface of wire exposed allows the heat to be well distributed, and thus the temperature is brought down below that at which the gas takes fire. The gas, of course, passes through the gauze readily enough, and so it is possible to light it above the wire gauze.

Davy recommended that all oil lamps used in mines should be encased in fine wire gauze (Fig. 69, GA), for although "fire damp" might enter along with air and might catch fire inside the lamp, the flame would not strike back and ignite the "fire damp" outside. Besides, the ignition of the "fire damp" inside the lamp would act as a warning that this colourless and odourless explosive gas was present in quantity in the workings. Where electric light is not used in the mines nowadays, the safety lamps are so constructed that the miners cannot open them; even if they try to do so, the lamps at once go out. The base of the lamp has usually a protected glass window (Fig. 69, G) to provide adequate light.

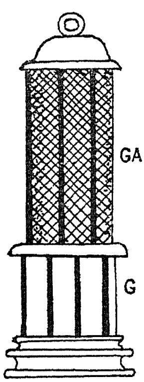

Fig. 69.—Safety Lamp.

Davy's safety lamps were at once brought into use, and proved a complete success. Save for a service of gold plate with which the grateful mine-owners presented him, he made no money out of his invention, although had he patented it he might have made thousands of pounds a year from royalties. A friend took him to task for this over-

generous behaviour, but Davy replied: "No, my friend, I never thought of such a thing. My sole object was to serve the cause of humanity, and if I have succeeded, I am amply rewarded in the gratifying reflection of having done so."

All these labours in physics and chemistry undermined Davy's health very considerably, and at one time it looked as if his illness might prove fatal. But he recovered and resumed his labours, though in a less strenuous fashion. In 1812 he was knighted, and the day after receiving the accolade he was married. The lady of his choice was a wealthy Scottish widow, who seems to have been the chief agent in making him forsake his beloved laboratory for a long continental tour, during which he met many of his famous fellow-workers in science in France, Germany, and Italy. For his invention of the safety lamp he was made a baronet, and, finally, President of the Royal Society, the highest scientific honour he could receive.

He had scarcely returned to work when he had an attack of apoplexy, and had once more to spend the winter abroad. He never returned, but died in Geneva in 1829, at the comparatively early age of fifty-one. On his tomb is engraved "Summus arcanorum naturæ indagator" (the greatest explorer of the secrets of nature), and he well merits praise so high.

Looking back over the life-stories of the great men of the past, it is surprising to note how few of them had parents who could afford to start their sons in life with a good education or to provide them with the wherewithal to gain it for themselves. Kepler was a potboy in a country inn; Galileo was an apprentice to a draper; even Newton was only the son of a small farmer; Herschel was a bandsman in a German regiment; Desmarest could hardly read when he was fifteen, and was fed and taught by the charity of the monks of Troyes; Watt was the son of a bankrupt shopkeeper; and even Davy, who died a baronet, loaded with all the honours his grateful countrymen could pour on him, began life as a bottle-washer in a country apothecary's shop. It is not necessary, therefore, to be born with a silver spoon in one's mouth—a wooden ladle may do as well—or to have been trained in the best school and university

in order to become a brilliant inventor or a distinguished man of science. One of our great writers, Anthony Trollope, makes a character in one of his novels pronounce the secret of success, "It's dogged as does it; it ain't thinkin' about it." Each of the great men we have mentioned, poor and, in most cases, ill-educated as they were, had a fixed idea in his mind as to what was to be his life's work, and perseverance and hard work did the rest. If this be true of many of the men whose acquaintance we have already made, it is doubly so of the man whose work we have now to study—Michael Faraday.

Michael Faraday.—Michael was the third son of a blacksmith who had married a crofter's daughter in Yorkshire, and who came up to London in the hope of mending his fortunes. But the times were very hard, and food was at a ransom. Michael, as a boy of five, had to live on one loaf a week! His father also was in bad health, and the family had at last to obtain relief from the rates. Michael seems to have mastered the "three Rs" at a day school, and spent the rest of his time, as he says himself, "at home or in the streets." "Home," by the way, was a couple of rooms over a coach-house in a mews near Manchester Square.

In 1804, when he was thirteen years old, he became an errand boy to a bookseller, and did his work so well that his master made him apprentice to the bookbinding trade without asking for a premium. Michael not only bound the books his employer gave him to work on, but read many of them as well, especially those that dealt with chemistry and physics. By the time he was nineteen he had managed to save enough out of his wages to pay for attendance at a course of lectures on physics, or natural philosophy as it was then called, and wrote out his notes of the lectures, illustrated by drawings of the apparatus used by the lecturer.

One of the patrons of the book-shop was a certain Mr. Dance, who happened to be a member of the Royal Institution, and this gentleman, being struck with Faraday's love of science, took the lad with him to hear Sir Humphry Davy lecture. Davy was a brilliant lecturer, and young Faraday came away enchanted. Bookbinding seemed now a detestable task, and

Faraday was prepared to do anything that might save him from the drudgery of sewing and gumming sheets of paper together from morn till eve. But what else could he do? He had no influential friends, not even Mr. Dance, for, having finished his apprenticeship, he had left the employ of the bookseller where he had first met him. But Faraday was not to be beaten. He took upon himself to write direct to Sir Humphry Davy, enclosing the notes he had taken of his lectures by way of showing what he could do. Imagine his delight when, a few days later, a carriage drove up to his door and a footman handed in a letter from the great man himself asking him to call at the Royal Institution. After the interview he was offered the post of laboratory attendant at a weekly wage of 25s., together with a bedroom in the Institution. Now his foot was on the first rung of the ladder, a ladder he never ceased ascending, until there were no more steps left for him to climb. He soon proved to Davy that in him the latter had found not only a keen and even enthusiastic worker but a genius of the highest order, and not many weeks passed before Davy made Faraday his assistant and private secretary. Some time afterwards, when Davy was asked what he considered to be his greatest discovery, he promptly replied, "Michael Faraday."

After his marriage in 1812, Davy set out on his continental tour, and he invited Faraday to accompany him, and thus the young scientist was given the opportunity of seeing something of the world and, better still, of meeting some of the great men of science in France and Italy. In spite of the advantages he thus gained, Faraday seems to have had fits of homesickness, for he wrote to one of his friends, "I fancy that when I set foot in England I shall never take it out again," and on his return journey he wrote to his mother: "At Deal we land on a spot of earth which I shall never leave again." His determination to stay at home in future was, however, not maintained, for twice afterwards he spent several months on the Continent.

The teacher in natural philosophy, whose lectures he had attended while he was working in the bookseller's shop, had meanwhile established a sort of club, called the "City Philo-

sophical Society," and of this body Faraday became a member, and to it he gave his first public address. Shortly afterwards he published, in the Journal of the Royal Institution, a paper on the composition of lime, and read another paper to the Royal Society on certain new chemical compounds. Faraday was now twenty-nine years old, and it was then that he began the researches that have made his name famous for all time.

Oersted, it may be remembered (p. 137), had found that when he brought a magnetic needle close to a charged wire, the needle moved from its normal north-south position to one at right angles to the direction of the current, and Ampère had found (p. 137) that whether the north pole pointed west or east depended on whether the wire lay below or above the needle. Faraday attempted to answer the question why this should be so.

Relation of Magnetism to Electricity.—Take an ordinary electric battery, and on the course of the wire joining the electrodes fix a piece of cardboard, on which sprinkle some iron filings (Fig. 70). On gently shaking the card the iron filings will arrange themselves in concentric circles round the wire, which are called "lines of force," and a magnetic needle can revolve round the wire. It occurred to Faraday that if a magnetic needle revolved round a charged wire, why should not a charged wire revolve round a magnetic needle? To test this he devised the following experiment (Fig. 71).

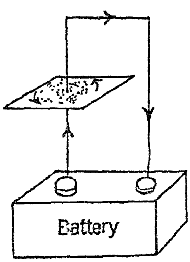

FIG. 70.—LINES OF FORCE.

He took two glass cups, A and B, and drilled holes through their bases to permit of the passage of the wires, J, K. The wire, J, ended abruptly just above the base of the cup, A, while K was continued upwards, as E, to the top of the cup, B. To the short wire he attached a metal rod, D, so that D was free to move in any direction. Above the two cups he fixed a rod with two knee-joints, insulated at C from the support, I. One leg, F, hung down into the cup, A, while the other had attached to it, by a fine wire, a metal rod, G, also free to move in any direction. Both cups were filled with mercury, H. The

current entered by J, passed on to D, through the mercury to F, down the hanging rod, G, through the mercury in B and E, and escaped by the wire, K. To his intense delight Faraday noticed that when the current was turned on, the rod, D, revolved round F, while G revolved round E. An onlooker tells us that Faraday became so excited that he danced round the table shouting, "There they go! There they go!"

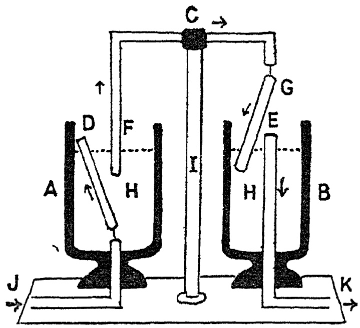

FIG. 71.—ROTATION OF ELECTRIFIED RODS. (See Text.)

The Induction Coil. — In order to understand Faraday's next discovery—one that had far-reaching results—it is necessary for us to know the meaning of certain terms used in electricity.

Electricity, as we have seen, can flow along a "conductor," and some substances, like silver, copper, nickel and graphite, are good conductors—*i.e.*, allowing the current to flow easily, while others will not carry the current at all, such as india-rubber, glass, or porcelain. These are used as "insulators," literally "island makers," forming impassable regions round the current. Porcelain cups are used as insulators for telegraph and telephone wires, such as may be seen on any telegraph pole. If we cover a copper wire with a sheath of rubber, we are really forming a tube by which we may transmit a current of electricity any distance we please, without any leakage taking place on the way. Air is a bad conductor, though not a perfect insulator; still it serves the purpose of such in the case of telegraph and telephone wires.

When a kettle boils, steam is produced, and when the lid is lifted off the steam escapes in volumes without appreciably pressing on the walls of the kettle. If we replace the lid and close the spout, leaving only a small hole in the lid, the steam cannot escape as freely as before, and it at once begins to exert pressure on the walls of the kettle and on the lid, while some of it issues through the hole in the lid with considerable force.

Thus we may allow steam to escape from the kettle in large quantity but at very low pressure, or in smaller quantity at high pressure. When an electric current passes along a conductor, it may be passing in large quantity at low pressure or in smaller quantity at high pressure. This analogy enables us to understand the difference between "ampèrage" and "voltage." Ampèrage corresponds to quantity flow, as when the kettle-lid is removed, and voltage to pressure flow—or what electricians call "tension" (potential)—as when steam can escape only through the hole in the lid. Hence we may have an electric current of high or low ampèrage and high or low voltage. The "ampère" is a unit of quantity, while the "volt" is a unit of tension or electromotive force (potential).

A current of electricity, however, will travel along a conductor only from higher to lower potential, forming what is called an "electric circuit." This circuit may be broken anywhere by introducing into its path a "switch." In every house lit by electricity switches are fixed to the walls of the rooms, by which it is possible to "turn on" the current and so to obtain light, or to "switch it off." If the cap covering one of these switches be removed, it will be seen that the outside handle operates on a lever whose free end is forked. The two prongs of the fork come into contact with two "terminals," to each of which is screwed the end of a wire, one carrying the current to the switch, the other carrying it away from it. Between the two terminals there is a gap too wide to allow the current to pass, for air is a bad conductor, until the gap is bridged by the forked lever.

Consider next another analogy. Suppose we attach a length of hose-pipe to a water tap in a garden from which we may obtain a plentiful supply of water. When the tap is turned on, the water flows out freely in a steady stream, and if the pressure in the main be sufficient, it may be projected for several feet. But suppose we desire to sprinkle the water over a flower-bed several yards away without wetting the paths or shrubberies lying between the end of the hose and the flower-bed, it may happen that the pressure is not sufficiently great to force the water so far. To gain our object we attach a nozzle

with a narrow outlet to the end of the hose, thus reducing the quantity of water driven out at a given time, but increasing the pressure on the aperture. The force with which the water is now squirted out enables it to jump over the intervening space. In a similar way, although an electric current carried by a wire from some source of supply may be great enough in amount—*i.e.*, in ampèrage—it may be too low in pressure—*i.e.*, in voltage—and hence it becomes necessary to introduce something that will play the part of the nozzle on the hose-pipe, to turn ampèrage into voltage. This apparatus is called an "induction coil," and this was Faraday's next discovery.

Ampère had found (p. 139) that when he surrounded a bar of steel with a coil of wire through which he sent an electric current, the bar retained the charge and became a magnet, but that if the bar was of soft iron it retained the charge only so long as the current was flowing. Electricity could thus be turned into magnetism, and Faraday, meditating on this fact, asked himself why could not magnetism be turned into electricity ?

In his first experiments he took a ring of soft iron, round each half of which he wound wires, X and Y (Fig. 72). One end of X was connected with one terminal of the battery, B; the other end, after being coiled round one-half of the ring, was connected with the other terminal of the battery, having on its course a switch, S. Similarly the other half of the ring had a wire wound round it, with a galvanometer, G, on its course. When the switch was closed a current passed through the wire, X, and back to the battery, but at the moment of closing the switch a current was set up, or "induced," in the wire, Y, and the needle of the galvanometer rotated in one direction and then came to rest. The same performance on the part of the galvanometer needle, though in the reverse direction, took place when the switch was opened; the galvanometer "kicked"

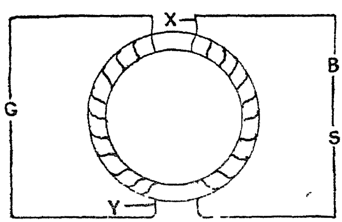

FIG. 72.—ELECTRO-MAGNETIC INDUCTION.

at every "making and breaking of contact," but showed no agitation while the current was actually flowing. Why? Faraday was unable to answer that question at the moment, but in 1831 he was more successful, and produced an apparatus by which an electric current was created by a moving magnet.

He wound several hundred yards of copper wire round a hollow wooden reel (Fig. 73, A), and connected the end of the wire with a galvanometer, G. He next took a bar magnet, B, and inserted it into the reel, and at once obtained a "kick" in the galvanometer needle in one direction, and when he withdrew the magnet, he obtained a "kick" in the opposite direction. During the time the magnet was inside the reel the needle remained at rest. If, then, a magnetic field can be produced, a current will be induced in the conductor every time it cuts the lines of force (p. 150) in the field.

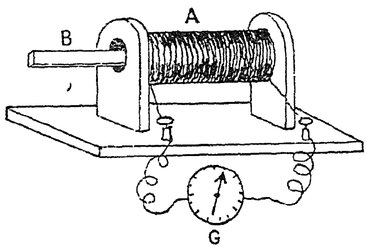

FIG. 73.—ELECTRIC CURRENT INDUCED BY A MAGNET.

Without going into any detail, the general principle of the instrument may be understood from Fig. 74. A is a bar of soft iron, or better, a bundle of soft iron rods tightly bound together, which, when a current is flowing through it, acts as a magnet, and round this bundle is wound a long length of thick copper wire, B. (For the sake of clearness the wires are very loosely wound, and only a few coils are shown.) The end, B, is connected with the source of the electricity, as is also the other end, C, after the wire has formed very many coils round the bundle. On the path of the incoming current there is a switch, S, or something that corresponds to it. This is called the "primary coil," and carries a current of high ampèrage, but of low voltage. It represents the stream of

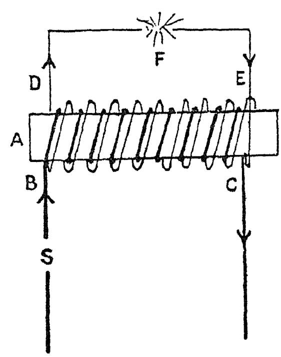

FIG. 74.—PRINCIPLE OF THE INDUCTION COIL.

water from the garden hose without the nozzle (p. 152). Outside the primary coil, and insulated from it, is wound a much greater length of thin copper wire in a far greater number of coils, the "secondary coil," D, E, and its free ends may be brought together at F, where there is a gap.

When the current of high ampèrage, but low voltage, passes through the primary coil, it transforms, as we have seen, the bundle of rods into a powerful magnet. The moment the circuit is broken at S, the bundle becomes demagnetised, and there is immediately induced in the secondary coil a current of low ampèrage but high voltage, sufficiently high to overcome the resistance of the air at F, and enable it to jump the gap between the two terminals and produce a spark. It represents the nozzle fitted to the end of the garden hose that enabled the water to be shot out to a considerable distance. If a rapid succession of sparks be required, we must "make and break contact" at S automatically by machinery. It is by such a piece of apparatus that the sparks are produced inside the cylinders of a motor-car engine, in order to explode the petrol mixture that takes the place of steam, the spark itself being transferred to the interior of the cylinder by what is called a "sparking plug." It was thus Faraday's genius that made the motor-car possible.

The Dynamo.—If a magnet be made to revolve inside a coil of wire, or, what comes to the same thing, a coil of wire be made to revolve between the poles of a stationary magnet, a current of electricity is induced in the wire, provided the wire cuts the lines of magnetic force at an angle. The current may then be collected by brushes, transferred to conductors, and employed for all sorts of purposes. This is the principle of the modern dynamo, but it is impossible to go into the very complex structure of the machine without taking up far more space than we can afford. Details must be studied in any one of the numerous works on electrical engineering; here we can deal only with general principles.

Measurement of Resistance—OHM.—In addition to the ampère and the volt there is another electrical term that is constantly met with in books on electricity—viz., the "ohm." The word is the name of a man, Georg Ohm, who was born at Erlangen,

in Bavaria, in 1789, the son of a locksmith. His father was a poor man—we had almost said "as usual"—but, fully alive to the value of education, he managed to send Georg and his brother to the university. After taking his degree, Georg became a schoolmaster and finally a lecturer on physics and mathematics in the Jesuit High School at Cologne, where he laboured for ten years.

Ohm's first work was to estimate the relative values of conductors, and for this purpose he experimented with wire made of different materials of the same sectional area, but of different lengths. He found that copper was the best conductor, and, reckoning its value at 1,000, he placed the other common metals in the following order: gold 574, silver 356, zinc 333, iron, 175 and lead 97. His figures are not very accurate according to our modern estimates, for the relative powers of electric conductivity are now given as: silver 1,000, copper 999, gold 800, zinc 299, iron 155 and lead 88. His chief error was in the case of silver, but the cause of that discrepancy from modern estimates was the faulty nature of the wire with which he experimented. Silver is the best conductor, but as it beats copper only by a mere fraction, and as it is so very much more expensive, it is scarcely ever used in electrical machines. After much experimental work Ohm was able to announce that the conductivity of a wire depended on three things: length, sectional area and material. If l represents length, a, sectional area, and ς be a value dependent on the material, then the resistance of a wire to the passage of a current, represented by R, is expressed by the formula $R=\frac{\varsigma l}{a}$—*i.e.*, the resistance varies directly with the length of the wire and the nature of the material, and inversely with the sectional area. Again, if C be the amount of the current and E be the force that sets up the difference in potential that makes the current go (what we now call the electromotive force, E.M.F., or E), R be the resistance offered by the wire, and r the resistance offered by the battery, then $C=\frac{E}{R+r}$. This is known as Ohm's law, and a resistance unit is spoken of as an "ohm," just as a quantity

unit is an "ampère" and an intensity or potential unit is a "volt."

Electrolysis.—It was only natural that Faraday should devote some attention to the subject in which his master, Sir Humphry Davy, had made his name—viz., electrolysis. Davy had decomposed potash and soda by means of a voltaic current, and obtained the metals potassium and sodium. Faraday showed that potash and soda could also be decomposed by a current derived from an ordinary friction machine. It was in his paper on this subject that he introduced the terms now in common use. Thus the terminals of the wires from the battery are called "electrodes," the positive being the "anode" (Fig. 75, A) or "up end," and the negative the "cathode" or "down end," C, the material split up is the "electrolyte," the element passing to the cathode the "cation," "ion" meaning "wanderer," and that passing to the anode the "anion."

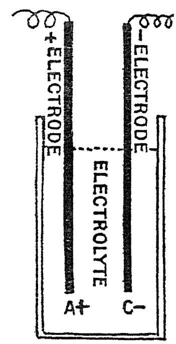

FIG. 75.—ELECTRICAL NOMENCLATURE.

After many experiments Faraday was able to state his law of electrolysis—viz., that the amount of chemical action taking place in the electrolyte depends solely on the amount of the electric current passing through it, and, conversely, the amount of decomposition of the electrolyte in unit time is a measure of the amount of the current. He pointed out that the same amount of current in ampères induces different amounts of decomposition in different electrolytes, and these amounts he called "electro-chemical equivalents." Thus, if a current of 1 ampère, acting on a compound of silver, deposits 4·025 grams of silver per hour, it will deposit 1·181 grams of copper from a copper salt in the same time, so that 4·025 and 1·181 are electro-chemical equivalents for these metals respectively.

Action of Magnetism on Polarised Light.—We have already referred to the curious optical effects discovered by Young and Fresnel in relation to crystals of Iceland Spar and tourmalin (p. 116), the phenomena of polarised light. Faraday took a deep interest in this subject, and endeavoured to find whether

magnetism had any influence on polarised light, and if so, what?

There is one thing that has struck all who have studied Faraday's work, and that is his wonderful insight and imagination, the almost prophetic power he had by which he was able to foresee the outcome of some quite simple experiment he happened to be conducting at the moment. When he read his paper on "The Magnetisation of Light" at the Royal Society he expressed one of these prophecies, and told his audience that he believed "that the various forms under which the forces of matter are made manifest have one common origin," and that he included light among them.

The particular experiment of which he then gave an account aimed at finding whether an electro-magnet has any influence on a beam of light passing near its poles. He used a powerful Argand lamp (*i.e.*, one where the wick is in the form of a hollow cylinder, so that air is admitted from below, feeding the flame both inside and outside), and polarised its light by reflecting it from a glass mirror. He then examined it after it had passed through the magnetic field. He tried changing the direction of the light, and used all sorts of media—glass of various kinds, Iceland Spar, tourmalin, etc.—but every experiment was a failure, the magnet seemed to have no effect whatsoever. In a final effort he tried a very heavy lead glass, which he had used sometime before for another purpose, and, to his delight, he got a rotation of the plane of polarisation, and this rotation was reversed when he reversed the current. He next used a charged coil of wire in place of the magnet and got the same result, so that there was undoubtedly some definite connection between light and electricity.

The next step was one that led to even more astonishing results, but these did not materialise till long after Faraday's time. He arranged a flame between the poles of a magnet and injected salts of sodium and lithium into it, and examined their spectra, but, alas! he obtained no result. But that was not the fault of the experiment, nor was it a flaw in his hypothesis, for where Faraday failed, another physicist, called Zeeman, armed later with much more powerful instruments, succeeded. We

shall return to this later on, when we consider some of the great discoveries made in our own time.

One final experiment before we leave Faraday and his wonderful works: "If iron," he said, "is magnetic, why not other substances?" If a bar of iron be swung between the poles of a magnet, it will place itself parallel to the lines of force—*i.e.*, in the line joining the north and south poles of the magnet. Faraday substituted a bar of heavy glass for the iron, and found, to his surprise, that it swung round until it came to rest at right angles to the lines of force, and so he concluded that all bodies may be divided into those that were para-magnetic—*i.e.*, those like iron which arranged themselves parallel with the lines of force, and dia-magnetic—*i.e.*, those which place themselves at right angles to these lines. Among the latter substances he classed human flesh, and concluded that if a man were suspended horizontally between the poles of a huge magnet, he would come to rest at right angles to the lines of force.

Although we have spent much time over Faraday and his discoveries, it is not too long when we take into account the enormously extended outlook he gave us into the wonders of Nature. We have learnt something of what he accomplished, but in telling of his work we have said little of the man himself since we left him as an assistant in Davy's laboratory.

Just after he began his study of Ampère's work on the effect of an electric current on a magnetised needle, he took unto himself a wife. There was no honeymoon, for he simply brought his bride home to his rooms in the Royal Institution and went on with his work as if nothing had happened. He was soon afterwards made Director of the Laboratories, but his salary remained at £100 a year, with rooms, fuel and light. During the years that followed he made a good deal of money in fees for advice given on various scientific problems that were put to him for solution. He soon began to feel, however, that if he was to work out the puzzles that Nature was constantly offering him, he must decline all outside work and all hopes of making a fortune. *We* are the wealthier by his discoveries, which led to so many and great inventions, but *he* died a poor man. In 1838 his health gave way, and for two

years he did practically nothing. In 1841 he went to Switzerland, where the rest and clear mountain air seemed to work wonders. During this time societies, universities and governments showered honours on him. He accepted these, but, at least at first, he declined a Civil List Pension of £300 a year, and it was only after urgent pressure that he was at length prevailed upon to accept it. His last years were peacefully spent with his wife in a house at Hampton Court, given to him by Queen Victoria. On one occasion, towards the end, an intimate friend visited him to ask after his health, when Faraday replied, "Oh, just waiting." The messenger with the sable wings called for him on August 25, 1867, and he now lies at rest in Highgate Cemetery:

> "Was ever man so simple and so sage, so crowned and yet so careless of a prize,
> Great Faraday, who made the world so wise, who loved the labour better than the wage."

Spectrum Analysis.—Before leaving the subject of physics a word or two must be said on a branch of it which, in recent years, has been enormously extended—viz., spectrum analysis. When a narrow beam of white light strikes a prism it is resolved into a band of coloured rays (p. 50), but we have already learnt that the visible spectrum is only a very small part of the entire spectrum (Fig. 52). In the visible part of the spectrum an English doctor, called Wollaston, in 1802, drew attention to certain dark streaks crossing the coloured bands, apparently indicating places where there was no light of any kind. More than ten years afterwards these dark streaks were rediscovered by Fraunhofer, an apprentice to an optician in Munich. Without knowing anything of Wollaston's work, Fraunhofer studied these dark lines, and gave them letter names. Fig. 76, A, gives the spectrum of sunlight, showing the position of the principal dark lines where Fraunhofer considered the sunlight was missing. After very careful examination he identified several hundreds of these lines, which are now always spoken of as "Fraunhofer's lines." Light from the moon or from Venus gave the same spectrum as light from the sun, but that was only to be expected, seeing that these celestial bodies shine only

by reflected light. But when he examined the great star, Aldebaran, he obtained a quite different spectrum (Fig. 76, C). At first Fraunhofer thought that it was the atmosphere surrounding our earth that blocked out some of the sun's rays, and naturally expected that light from a star would be affected in a similar manner. But seeing that this was not so, and knowing that Aldebaran shone by its own and not by reflected light, he concluded that sunlight must be different from star-light.

The next step was taken in 1827 by the astronomer Sir John Herschel, and was based on the fact that if table-salt be

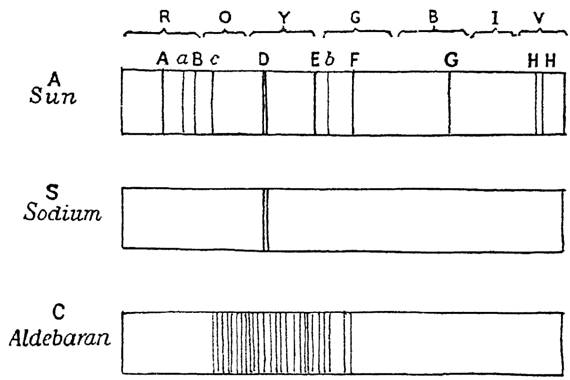

FIG. 76.—SPECTRA WITH ABSORPTION LINES.

placed in the flame of a spirit-lamp the flame becomes bright yellow, and when this light is examined through a spectroscope it shows a bright yellow double streak at the point of Fraunhofer's dark line, D, due to the metal sodium in the salt. Herschel suggested that if the bright lines given by luminous vapours were carefully mapped out, these, if constant, might be utilised for the identification of the same substances wherever they might occur. After a large number of metals had been examined in this way, Herschel's idea was found to be entirely correct. No matter how many other substances are present, and no matter how minute the quantity of the material used, the spectrum lines belonging to that particular substance can always be identified. It may readily be imagined what a valu-

able method this was likely to become, not only for identifying the faintest traces of known elements, but also for discovering new ones, and it was actually by means of the spectroscope that several new metals were found, such as cæsium, rubidium, indium and gallium. The whole matter was very carefully studied and explained by two distinguished German scientists, Bunsen and Kirchhoff.

The Bunsen Burner.—Robert Bunsen was born in 1811, and, after holding teaching posts at Cassel, Göttingen and Marburg, became professor of chemistry at Heidelberg in 1862, where he remained until his death in 1899. His name is best known, perhaps, as the inventor of the "Bunsen burner," without which no chemist can carry on his work. If a substance be burnt in an ordinary gas or oil flame there is always formed on it a deposit of soot due to the incomplete combustion of the gas or oil. Bunsen's invention consisted in placing a metal tube over an ordinary gas-jet, the bottom of the tube being pierced with holes to permit of air entering and mixing with the gas before being lit at the top of the tube. In this way complete combustion was effected and a non-luminous flame resulted (Fig. 77).

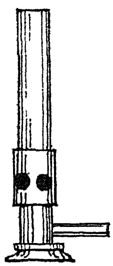

FIG. 77.—BUNSEN BURNER.

Gustav Robert Kirchhoff was born at Königsberg in 1824, and became professor of physics first at Heidelberg and afterwards at Berlin, where he died in 1887.

The Spectroscope.—It was in 1859, while the two men were fellow-professors at Heidelberg, that they worked out the whole theory of spectrum analysis. The general principle of the spectroscope is shown at Fig. 78. T is a telescope (fixed collimator) having at one end a narrow adjustable slit, S, which receives the beam of light, and at the other end a lens, L. A, A′ are prisms by which the rays are refracted. This enables the spectrum to be spread out as a long band, and by shifting the position of the movable telescope, T′, any part of the spectrum may be brought into the field of vision. Thus white light, for example, appears as a "continuous spectrum," violet to the left and red to the right, when such white light is transmitted

through the slit, S, and examined by the eyepiece, E. Sodium light, on the other hand, is monochromatic (see Fig. 76, S).

Kirchhoff allowed a bright ray of sunlight to pass through the vapour of sodium, and found that the dark Fraunhofer line, D, appeared even darker than it was in the solar spectrum, and concluded that the sunbeam must have come through the vapour of sodium before reaching the earth, and that this vapour must be in the solar atmosphere, seeing that there is none of it in our own. In every case that he tried he got the same result, and so he was led to the general conclusion that any glowing or incandescent vapour absorbs from white light those rays that it itself gives out when glowing. Now since Fraunhofer had shown that the light from a star may differ

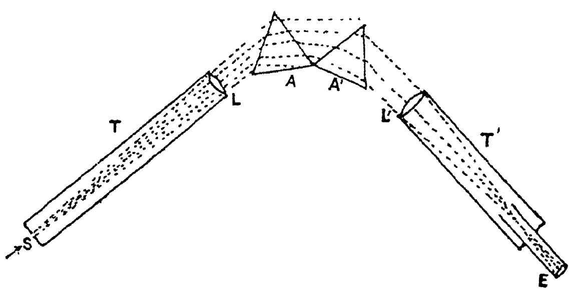

FIG. 78.—SPECTROSCOPE.

from the light from the sun, the starlight must have passed through other incandescent vapours between the star and our eyes. It would thus be possible to determine what were the vapours that surrounded the star and the sun respectively.

Sir William Herschel thought that the sun was a dark globe surrounded by a glowing atmosphere, but Kirchhoff's discovery proved that, on the contrary, the sun was an intensely hot burning mass, surrounded by an envelope of incandescent vapour. By employing spectrum analysis we have learnt that, although many of our common elements (about forty) are present in the sun, such as hydrogen, oxygen, carbon, iron, copper and silver, yet there are many other equally common ones that do not seem to be there at all, such as sulphur, phosphorus, mercury, nitrogen and gold; they are probably there, however.

Discovery of Helium.—One of the most remarkable of the discoveries that have resulted from the use of the spectroscope is that made by the British astronomer, Sir Norman Lockyer, in 1868. He noticed a fine yellow line close to the double sodium pair, and since no other substance known to science gave this line, he concluded that he had found a new element. To it he gave the name of "helium," the sun element, from the Greek word for the sun, *helios*. Twenty-seven years later another British scientist, the late Sir William Ramsay, while examining a rare Norwegian mineral called clèveite, got from it a gas which gave the same spectrum line as helium, so that we have here an instance of an element identified in the sun, 93 millions of miles away, many years before it was discovered on the earth. Helium is what is called an "inert gas," because it refuses to combine with any other element. It is non-inflammable and of low density, and hence is invaluable for inflating balloons. During the early days of the Great War balloons for observational purposes were filled with hydrogen; but these, of course, could be instantly destroyed by a well-aimed shell. By and by great stores of helium were found both in the United States and in Canada, and, had the war not come to an end, there is no doubt that dirigibles would have always been filled with helium instead of with the inflammable hydrogen.

Another advance was made in the subject when the English astronomer, Huggins, began examining the spectra of stars and nebulæ, but into his work we need not enter at present, as the results achieved belong rather to the later years of the nineteenth century.

Here we must leave our study of physics for the time being and turn to the closely related science of chemistry, which we left in a rather backward state at the end of the seventeenth century. After that period it began to push on at a tremendous pace, until, today, it is perhaps the most forward of all the sciences.

§ iv. Chemistry

When we review the history of chemistry and try to realise the condition of the science in the seventeenth century, what amazes us most is the almost entire absence of any clear idea as to the essential difference between an element and a compound. As modern methods of separating one partner in a compound from another were entirely unknown, there were very many substances that were regarded as elements by the early chemists which were, later on, found to be compounds, such as lime, potash, soda and magnesia.

The Balance in Chemical Experiments—Joseph Black.—The first chemist of the newer school was Joseph Black, the discoverer of the law of latent heat (p. 119). He was the first to introduce the general use of the balance into chemical manipulations. Before his time men were content with proving the presence or absence of a substance in any mixture—that is to say, they were satisfied with *qualitative* tests; but Black insisted on the necessity for making *quantitative* measurements as well, and nowadays the "balance room," fitted with instruments of great precision, is regarded as an essential part of every chemical laboratory.

Discovery of Carbon Dioxide.—One of Black's investigations was concerned with the nature of limestone, in the course of which he made some extremely important discoveries. These may be repeated with the aid of very simple apparatus, costing only a few pence.

Obtain some limestone and put a small piece into a test-tube containing some water. Nothing happens; but add a few drops of "spirit of salt," or what we call hydrochloric acid, and at once bubbles of gas are given off from the limestone, and this effervescence continues until all the limestone or acid has disappeared. Take another piece of limestone and heat it to redness; it becomes after a time a porous solid, which no longer effervesces with acid, but, on the other hand, if water be added it swells and becomes hot. From these very simple experiments we learn, first, that limestone is insoluble in pure water, but is acted upon by an acid with the loss

of a gas, leaving something behind which is soluble in water. Second, we learn that heat alters the limestone in such a way that the substance left gives off no gas when treated with the acid, but changes into something else when water is added. We explain these facts nowadays thus:

Limestone is a compound of carbon, oxygen and the metal calcium, namely calcium carbonate ($CaCO_3$), which is not soluble in pure water. When treated with hydrochloric acid (HCl), a compound of hydrogen and chlorine, the action results in the formation of three substances, water (H_2O), the gas carbon dioxide (CO_2), found in the "choke-damp" formed in coal-mine explosions (p. 145), and a new substance, calcium chloride ($CaCl_2$), partly derived from the hydrochloric acid and partly from the limestone. Chemists write this change thus:

$$CaCO_3+2HCl=CO_2+H_2O+CaCl_2$$

meaning that one molecular unit of limestone with two of hydrochloric acid give one unit each of water, carbon dioxide and calcium chloride. This is what chemists call a "chemical equation," and, as matter is neither created nor destroyed, everything on one side of the equation must appear on the other. If this equation be carefully studied it will be seen that on both sides there are three Os, two Hs, two Cls, one Ca and one C, although differently arranged. These symbols, O, H, C, Ca and Cl stand for the chemists' atoms (see p. 184).

When limestone is heated an invisible gas is given off, and there is left "quick" or active lime. Chemists represent what happens by this equation: $CaCO_3=CaO+CO_2$. Nothing has been added to the limestone, for heat, as we know from Count Rumford's work (p. 122), is not a substance, and hence does not appear in the equation. The gas given off is carbon dioxide, and the "quicklime" is a compound of calcium and oxygen only. When hydrochloric acid is added to quicklime there is no effervescence, because there is no carbon dioxide to be given off. When water is added to the "quicklime" (CaO), the latter at once begins to swell, heat is produced, and steam is given off, as may be seen where workmen are mixing lime and

water to make mortar. What is happening in this case is not a breaking down or decomposition, but a construction or combination. Water and quicklime chemically unite to form "slaked" or satisfied lime, thus:

$$CaO + H_2O = CaH_2O_2 \text{ or } Ca(OH)_2.$$

If slaked lime be shaken up in water, some of it will dissolve, and the clear solution is sold in the shops as lime-water. Breathe through this lime-water and it becomes milky. Now when the white particles have settled to the bottom of the vessel as a sediment or "precipitate," pour off the excess fluid, dry the sediment, add a little dilute hydrochloric acid, and once more carbon dioxide is given off and the white powder disappears. In short, we have got back to where we started, for the sediment is calcium carbonate, the carbon dioxide having come from the breath and united with the lime.

These mysterious changes, taking place in a substance supposed, in Black's time, to be an element, were very puzzling to the chemists of the eighteenth century, and Black set himself the task of solving the riddle, and attacked it in the following way. He weighed some pieces of limestone and placed them in a flask (Fig. 79, A) along with water, to which he added some acid, and by means of a bent tube, B, connected the flask with a receiver, C, filled with water and standing mouth downwards, over a trough full of water, D. The gas (CO_2) which collected in the vessel, C, was found to be the same in nature and amount as that got by heating chalk or limestone. Similar experiments with "magnesia alba" gave the same gas.

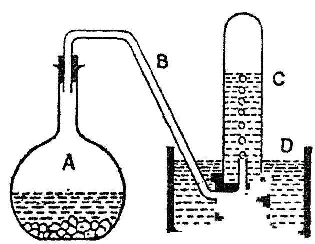

FIG. 79.—FORMATION OF CARBON DIOXIDE FROM LIMESTONE.

He next took some lime-water and bubbled the gas through it and obtained a white precipitate, which he proved to be identical with limestone or chalk. Since the gas was originally "locked up" in the limestone, he called it "fixed air," and was

thus able to show that limestone was not a simple substance but a compound of lime and "fixed air." When he inserted a lighted taper into a vessel with "fixed air" it went out. He also collected the same gas from fermenting malt and certain mineral springs, as well as from air expired from the lungs.

Robert Boyle had long previously obtained a blue pigment from a lichen (*Lecanora*), which is known as litmus, and which has the property of becoming red whenever it is brought in contact with an acid. By using a solution of litmus, a Swede, called Bergman, showed that "fixed air" was an acid, and finally, in 1779, the great French chemist, Lavoisier, proved that "fixed air" was a compound of carbon and oxygen, and renamed it carbonic acid.

The Phlogiston Theory.—During the seventeenth and most of the eighteenth centuries, nearly all scientific men believed in what is known as the "phlogiston theory" (p. 56)—viz., that combustible bodies consisted of an invisible substance called "phlogiston" and an ash or "calx," and that the more phlogiston there was in any body the more combustible it was. It may be safely said that this chimera retarded progress in chemistry for at least a hundred years. It was quite on a par with that equally erroneous notion that heat was a "subtle fluid," disposed of by Rumford and Humphry Davy. But both these theories were generally accepted during the period we have mentioned.

Joseph Priestley.—At this time there lived a man who had been justly regarded as one of the founders of chemistry, but who might have earned even greater merit had he only recognised what a "will-o'-the-wisp" phlogiston really was. This was Joseph Priestley. Like so many other great men, he came of a humble stock, for his father was a cloth-dresser in a mill near Leeds, where Joseph was born in 1733. In his youth he showed a considerable gift for learning languages, and so his family chose for him the clerical profession. After his training for the ministry was completed, he became a nonconformist parson in a village in Suffolk. His congregation, however, did not approve of his theological principles, and so he left Suffolk for a corresponding post in Cheshire, finally

becoming a teacher of languages at Warrington Academy. After six years in that town he returned to the ministry as the pastor of a chapel in Leeds. During all this time, in addition to carrying on his clerical and other duties, he had been devoting much of his energy to mastering what was then known of the sciences of physics and chemistry. It was while he was at Leeds that he published the first volume of his great work called "Experiments and Observations on Different Kinds of Air."

Priestley was very skilful in inventing apparatus. Recognising that bladders were unsuitable articles in which to collect gases, he brought into use glass cylinders, which he filled with water or mercury, afterwards to be displaced by the gas to be examined. This was called a "pneumatic trough," used by Black, but also by Priestley in 1772, five years before Black published his work on "fixed air." Carbon dioxide was known to be present in large quantities in certain mineral springs, and Priestley pointed out that the exhilarating effect of these waters was due to the presence in them of this gas which could be made to dissolve in ordinary water under pressure. When small quantities of potash and soda were added, a refreshing drink was obtained, and this was the starting-point of the great industry of mineral water manufacture so familiar to us today.

Priestley remained in Leeds for six years, but left that city to take up the post of librarian to Sir William Petty, afterwards the first Marquis of Lansdowne. This nobleman had been one of the Secretaries of State, but had recently resigned owing to differences of opinion with the other members of the Government over the policy to be followed with regard to the American colonies. The Marquis was deeply interested in scientific matters, and Priestley, now with a comfortable home and an adequate salary, had abundant opportunity for carrying out research work, in which his patron aided him in every way possible. Among other advantages derived from his friendship with the Marquis was the opportunity of meeting other famous chemists, especially Lavoisier, whom they visited during a tour on the Continent.

Discovery of Oxygen.—Let us now turn to the discovery with which Priestley's name is almost always associated—viz., the discovery of oxygen gas.

Exactly one hundred years previously, the young Oxford doctor, Mayow, had shown that only a portion of any measured quantity of atmospheric air was used up by a burning candle or a living animal enclosed in a vessel containing air, and thus realised that this proportion of the atmosphere was essential, both to combustion and to respiration. Mayow called it "spiritus nitro-æreus." It is true he did not actually prepare it, though had he lived there can be little doubt that he would have done so.

Priestley, on the other hand, has the credit of actually isolating the gas. He used a pneumatic trough (Fig. 80, A) filled with mercury, in which he arranged a vessel, B, also filled with that metal. In the bulb of the retort, C, he placed a quantity of red oxide of mercury, and then concentrated solar rays on it by means of the lens, D. Presently the mercury oxide began to give off a gas which collected in B, while glittering drops of mercury made their appearance in the retort. He thus proved that red oxide of mercury was a compound of the metal mercury and a gas, which, instead of extinguishing a lighted taper, made it burn more brightly. Finding also that a mouse enclosed in a bell-jar of the gas became more lively, he concluded that it could not be injurious to health, and therefore decided to breathe the gas himself. He felt so elated from its effects that he said, "Some day soon this will be a fashionable luxury."

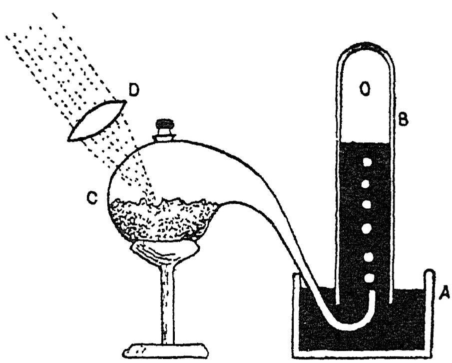

FIG. 80.—PRIESTLEY'S METHOD OF ISOLATING OXYGEN GAS.

Although Priestley (in 1774) had thus really isolated oxygen,

he missed the most important consequence of his discovery by his persistent belief in the phlogiston theory. He even went so far as to call the new gas "dephlogisticated air"—that is to say, air that would not burn because it had been deprived of its phlogiston.

Priestley remained with the Marquis of Lansdowne for seven years, but afterwards returned once more to clerical work, this time in Birmingham. While engaged in these chemical investigations, he found time to write books and pamphlets on theological subjects, and on the relations of Church and State, and made himself much disliked by his outspoken views. When he got the length of expressing publicly his sympathy with the French Revolutionists, matters came to a crisis. He was so unpopular in the midland capital that his house was burnt to the ground by an infuriated mob, and he and his family barely escaped lynching. He thereupon removed to London, but even there his unpopularity pursued him, and at length he crossed the seas to the New World, where he died in 1804.

Scheele.—While Priestley was experimenting with red oxide of mercury and investigating oxygen gas, a Swedish apothecary, called Scheele, was working on the same subject. Towards the end of the eighteenth century the means of communication between workers in science was not what it is now. Today, if a man makes a great discovery, it is known all over the world in a few hours, even in a few minutes if it be "broadcasted." The newspapers tell their readers about it the next morning, and the story is given in full to some learned society within a few days, or at most a few weeks. It was not so in 1774 when Priestley discovered oxygen. Scheele had been experimenting on gases for some years, quite unaware of Priestley's doings, as Priestley was ignorant of Scheele's work. Both published their results in book form, Priestley in 1774 and Scheele in 1777, so that Priestley has the credit of being first in the field. It is true that his book came out three years before Scheele's "Chemical Treatise on Air and Fire," but there is every reason to believe that Scheele had isolated oxygen at least two years before Priestley did. The whole story

of Scheele's life and labours was, indeed, very imperfectly known until the Swedish Academy gave it to the world in 1892.

Carl Wilhelm Scheele, who was born in 1742, was one of a family of eleven, and his opportunities for acquiring knowledge were few. At the age of fourteen he became apprentice to an apothecary in Gothenburg, and taught himself chemistry with the aid of the books and apparatus he found in his master's shop. Indeed, the story of his early life much resembles that of Humphry Davy, who was also an apprentice to a pharmacist, and who also taught himself chemistry very much in the same way (p. 140). Davy became a very distinguished man both in science and in society, but Scheele never rose above his humble beginnings as a country apothecary. There was no Count Rumford in Sweden to offer him a post in a great scientific institution, where his genius might have had full opportunity of developing, and where wealth might have provided him with the apparatus he required.

When he had reached the age of twenty-six he removed to the capital, but still as an assistant in a "chemist's" shop. His first work was the production of an inflammable gas by immersing iron filings in dilute acid. At that time iron was supposed to be a compound of a calx and a little phlogiston, according to those who held the phlogiston theory, of whom Scheele was one. He thought that in the inflammable gas he had produced from the mixture of iron filings and acid he had at last captured the mysterious phlogiston, and called it "phlogiston elasticum"; what he had really discovered, although he did not know it, was hydrogen.

Scheele's Discovery of Oxygen.—In 1770 Scheele went to Upsala, where he made the acquaintance of Bergman, who was at that time professor of chemistry in the university there. It was he who showed that Black's "fixed air" was an acid, but otherwise he was not one of the leading lights in the science. It was at Bergman's instance that Scheele began to examine what the Roman historian, Pliny, had called "black magnesia." From this substance, which is really an oxide of the metal manganese, Scheele obtained oxygen. There are several compounds of manganese and oxygen, and related to them is a salt

called permanganate of potash which yields up its surplus oxygen very readily in the presence of putrefying organic matter, removing its offensive odour almost at once. When dissolved in water, in which it is very soluble, it forms a very beautiful violet solution, often used for staining floors. Sodium permanganate is now sold as a disinfectant under the name of "Condy's Fluid." Scheele obtained oxygen from several other substances, and, incidentally, isolated not only manganese but also the metal barium and the gas chlorine, afterwards identified as an element by Sir Humphry Davy.

The only honour Scheele ever received was that of being made a member of the Royal Academy of Sciences, an honour he richly deserved. The last few years of his life were spent in the little country town of Köping, where he died in 1786, at the early age of forty-four.

HENRY CAVENDISH.—We must now turn our attention to a person of a very different character, a member of one of England's best-known families, the House of Devonshire. The Hon. Henry Cavendish is celebrated in science not only as a chemist but also as a physicist, for by an ingenious apparatus he was able to measure the density of the earth, and that to within a fraction of the result obtained by modern physicists, using his method, but with much more delicate instruments. We shall return to this subject later when we speak of the discoveries made in our own time (p. 348).

Notwithstanding the fact that he came of such notable parentage and made so great a name for himself in science, it is remarkable how little we know about him. He was extraordinarily reserved and retiring, mixing with very few people. He never spoke to his servants if he could possibly help it, and was even in the habit of leaving a note on the hall table saying what he wished for dinner! He was a very wealthy man, and although he gave liberally when he was asked to do so, he never tried to find out deserving cases of poverty for himself. When he did give, his gift was seldom accompanied by the little kindly sympathy that would have doubled its value. A friend of his once said, "Cavendish did some good in a very ungracious manner." His love of solitude and his abhorrence of fuss and

ceremony was almost a mania with him, and nothing illustrates this hermit-like characteristic better than the story told by his doctor, who records that one evening, when Cavendish was very ill, he dismissed his valet, saying that he did not wish to be disturbed as he had something very important to think about. It was something he—and we—have to think about only once, for he died before morning!

The problems at which he used to work were, when finished, as often as not, put away in pigeonholes and never looked at again, an idiosyncrasy he shares with Sir Isaac Newton, who had a similar habit of hiding the results of his researches.

Cavendish was born in 1731, and educated at a private school, and afterwards at the University of Cambridge, where there is now a memorial to him in the form of the Cavendish Physical Laboratories. Little is known as to how he spent his time between the date of his leaving Cambridge in 1753 until 1766, when he published a paper on gases in the Transactions of the Royal Society, and for many years afterwards he appears to have been engaged on research on similar subjects. It was not until 1784, however, that he made his great discovery of the composition of water, which he announced in his work called "Experiments on Air."

The Composition of Water.—Cavendish had already studied the properties of "inflammable air" or hydrogen, and made use of the knowledge he had gained in his later experiments. He obtained hydrogen by pouring dilute sulphuric acid over zinc, and collecting the gas given off by means of a pneumatic trough (p. 169). When he mixed a measured volume of this gas with about two and a half times its volume of ordinary air and set fire to the mixture, an explosion took place, and the wall of the container became dim with dew, which he identified as water.

In order to determine the exact proportions of the two gases he invented an instrument which he called a eudiometer (Fig. 81). He prepared a mixture of 195 volumes of oxygen and 370 volumes of hydrogen in a bell-jar, and, from this reserve, filled the pear-shaped bulb, A, of the eudiometer, from which he had previously extracted all the ordinary air by

an air-pump. The tap, B, was then closed, and an electric spark was sent through the terminals, C C. In his own words he said the gas "lost its elasticity and became liquid water." This on condensation gave room for more of the gaseous mixture, and that was again fired and changed into water, and so on, for six times in succession. The water so formed was produced by the chemical union of 2 volumes of hydrogen with one volume of oxygen, but it was distinctly acid. This impurity he identified as nitric acid caused by the accidental presence of nitrogen. Nitrogen was the gas left over from ordinary air after the oxygen had been removed by combustion. It had been noted by Mayow in his experiments (p. 58), and had been called "mephitic air," in 1772, by a chemist named Daniel Rutherford. The word is of Greek origin, and means a "poisonous exhalation," but we speak of it now as nitrogen. It is called in Cavendish's book "phlogisticated air," and a careful analysis proved to him that the nitrogen was not pure, but that a small proportion, which he estimated at one-hundred and twentieth of its volume, consisted of something else, the nature of which he was unable to determine. His final analysis gave the composition of atmospheric air as 20·833 per cent. by volume of oxygen and 79·167 per cent. of nitrogen, the latter figure including the unknown "impurity." More than a century afterwards Lord Rayleigh and Professor Sir William Ramsay discovered its nature (chiefly argon), and incidentally added several new elements to the growing list. The proportion of these together came to about 0·94 per cent. of any given volume of nitrogen, so that Cavendish, with his much cruder apparatus, made a very close approximation to the estimate arrived at today with the most delicate instruments modern scientific workshops can produce.

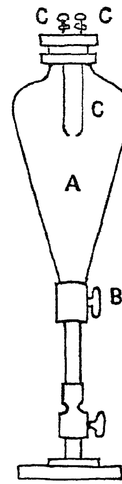

FIG. 81.—CAVENDISH'S EUDIOMETER.

During the latter half of the seventeenth century and the whole of the eighteenth, facts of chemistry were thus rapidly accumulating, but isolated facts, as we have already said, do

not make a science, they must be woven into a connected whole. Moreover, the nomenclature of chemistry was largely in a state of chaos; indeed, the whole subject awaited a master hand to mould it into shape, and do for it what Newton did for astronomy and Hutton did for geology. This master was forthcoming in the person of Antoine Laurent Lavoisier.

Lavoisier.—Lavoisier was born in 1743, and was the son of a lawyer, and he himself was educated with the view of following the same profession. But the lure of science was too great, and by the time he had reached his twentieth year he had forsaken the study of law for that of chemistry. Experimental science in general and chemistry in particular required apparatus, and apparatus, especially in those days, was costly, so that, although his family were by no means poorly off, Lavoisier had to earn an income somehow. At first he was Director of the Government powder works, but shortly afterwards he became a member of a sort of syndicate, called the "Ferme Générale," which had for its purpose the collection of taxes on foreign and imported goods, paying the Government a certain sum annually for the privilege of doing so. The Government was thus relieved of the labour of gathering these taxes, and was assured of a definite income from the Ferme, while that body benefited by all profits it made on the transaction. That the profits were considerable is shown by the fact that most of the men of the syndicate lived in great luxury and, by their extravagance, roused popular indignation against them. There is no reason to believe that Lavoisier acted as a tax collector in any but an honest and kindly way, and whatever he made out of his post he devoted to the purchase of apparatus and the equipment of his laboratory. Nevertheless, he did not escape the hatred of the taxpayers, a hatred that was ultimately to lead to his death.

When he was twenty-eight years old Lavoisier married a girl of fourteen, who was the daughter of one of his colleagues in the Ferme. Mere child as she was she showed herself to be possessed of a remarkable brain, and used it to assist her husband by translating chemical treatises in other languages into French, and in sketching and engraving apparatus to illus-

trate his writings. Many years afterwards she became the wife of Count Rumford, but that second marriage, by all accounts, was not a success.

One of the last of Lavoisier's public services was connected with the Commission that devised the metric system of weights and measures, now universally used in science. He also took a keen interest in the affairs of the Academy of Sciences, which corresponded to our Royal Society of London, but, in 1793, the National Convention suppressed all the learned societies, and all the members of the Ferme Générale were arrested and imprisoned shortly afterwards. A special appeal was made on behalf of Lavoisier as being a distinguished scientist who had, by his work, not only done good service to the State but had conferred great glory on France by his discoveries, but the appeal was of no avail. One of his judges at the trial brutally remarked, "Scientists! The Republic has no use for scientists." A few hours afterwards he was hurried away to his execution. The great mathematician, Lagrange, said of this judicial murder, "A moment was all that was necessary in which to strike off this head, and probably a hundred years will not be sufficient to produce another like it."

Lavoisier's Use of the Balance.—We have already seen that one of Black's chief merits was his constant use of the balance, by means of which he obtained accurate quantitative results where his predecessors had been content with qualitative ones only (p. 165). Lavoisier fully recognised the value of the balance, and in all his researches brought it into play wherever he could. He was the first to introduce the chemical equation to represent every chemical change, and to insist that the two sides of the equation must exactly balance each other.

It was an ancient belief among chemists that water could be transformed into earth, but this Lavoisier proved to be perfectly erroneous in the following way. He used a vessel of known weight, called from its shape a "pelican," a flask with a long neck bent over in a loop so as to re-enter the flask at a lower level. Into this he introduced a measured quantity of pure water, sealed the flask, and applied gentle heat. The water vapour produced passed over into the narrower part of the

vessel, where it condensed and trickled back into the bulb. After three months of continuous heating he evaporated off all the water and obtained a small sediment, which he collected and weighed. The empty "pelican" was also weighed, and it was found that the weight of the sediment was exactly equal to the weight the vessel had lost. The only possible conclusion was that the water, unchanged in itself, had dissolved some part of the glass itself.

Lavoisier's Completion of Priestley's Work.—During their visit to the Continent, Priestley and his patron, the Marquis of Lansdowne, made Lavoisier's acquaintance, and Priestley told him how he had obtained "dephlogisticated air" by heating red oxide of mercury. Lavoisier at once set to work on the problem of determining the nature of the gas that had been isolated by Priestley, repeating his experiments, but in the reverse way —*i.e.*, by causing "dephlogisticated air" to unite with mercury, under quantitative conditions (Fig. 82).

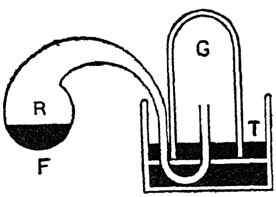

FIG. 82.—OXIDATION OF MERCURY.

He placed 4 ounces of mercury in a retort, R. The retort had a bent neck opening into a bell-jar, G, standing over mercury in a trough, T. He calculated the volume of the air in the retort and bell-jar, and found it to be 50 cubic inches. He then heated the retort by means of the furnace F, and presently saw a reddish scum appearing on the surface of the mercury. He kept the experiment going for twelve days, until the formation of the red scum had ceased, and then proceeded to measure and weigh the products. He first of all found that there were now only 42 cubic inches of gas in the retort and bell-jar, while the red scum weighed 45 grains. Placing these 45 grains in another retort and heating it, as Priestley had done, he obtained 41½ grains of mercury and 8 cubic inches of gas. The 42 cubic inches of gas left over from the first experiment he found to consist of "mephitic air," or, as he called it, "azote" (from the Greek words "*a*," not, and "*zoe*," life), since it could not support life, while the 8 cubic inches of gas obtained from the second

experiment was "dephlogisticated air," or what Lavoisier at first called "vital air," since life was impossible in its absence. When the 42 cubic inches of "azote" and the 8 cubic inches of "vital air" were mixed together he obtained the 50 cubic inches of atmospheric air with which he started. The cycle was thus complete.

The New Chemistry.—After numerous experiments of a similar nature, he put forward four general principles or laws as the basis of his new chemistry. The first was that substances burn only when "vital air" is present. His second proposition was that all non-metals, such as phosphorus, sulphur, or carbon, when burnt in vital air, give rise to acids, phosphoric, sulphuric, or carbonic, and for that reason he renamed his vital air "oxygen," from the Greek words: *oxus*, tart or acid; and *gennao*, to produce. In this second generalisation he was over-hasty, for hydrochloric acid, HCl, contains no oxygen. Lavoisier's third principle was that a metal when burnt in air formed a calx by combining with oxygen, becoming heavier in the process. Thus, when the metal magnesium is ignited in oxygen it produces a white powder, magnesia, which is heavier than the original magnesium by the weight of the oxygen it has fixed from the air. Lastly, he affirmed that there was no such thing as phlogiston, and that every case of combustion was due to the union, under proper conditions, of the combustible body with the oxygen of the atmosphere. The phlogistonists did not give in without a struggle, but Cavendish's synthesis of water from hydrogen and oxygen drove the last nail into the coffin of phlogiston, and the new century knew the name no more, save in an historical relation.

In the year 1789, just five years before chemistry lost her new prophet, Lavoisier published his famous "Elementary Treatise on Chemistry," in which he expounded his views on the science in general, views that are now universally accepted, This book resulted in a complete change in the nomenclature of the science. "Inflammable air" became hydrogen—the water producer; "phlogisticated air" became nitrogen, since its union with oxygen—the acid producer—gave nitric acid. Compounds of oxygen with metals were known as oxides which,

when united with acids, formed salts. Moreover, since oxygen united with sulphur, phosphorus, and so on in varying proportions, the terminations of the names of these acids were altered to suit. Thus sulphur with relatively more oxygen gave sulphuric acid, and with less gave sulphurous acid; similarly for nitric and nitrous acids and phosphoric and phosphorous acids. The salts of these acids were respectively sulphates and sulphites, nitrates and nitrites, etc. In short, the whole vocabulary of chemistry took the form that we are so familiar with in the textbooks of the present day.

It is seldom, indeed, in the history of science, that so great a revolution has been brought about by the publication of one comparatively small book. Even in the almost unexplored domain of organic chemistry Lavoisier pointed out the way to be followed; for he realised that it was possible here also to work backwards, so to speak, and by carefully weighing the products obtained from the combustion of substances like alcohol or sugar, to determine how much carbon, hydrogen and oxygen was in the original substance, and to reconstruct it—at least, on paper.

The early years of the nineteenth century, therefore, saw an entire change in the outlook on chemistry. Lavoisier's work had almost at once caused the evaporation of the mists that had for so long clouded the whole subject of chemical combination, and now it was possible to follow all the changes in the test-tube or retort with a clear vision of what was taking place. Phlogiston was seen to have been merely a will-o'-the-wisp, leading the student into a morass in which he was doomed to flounder hopelessly. Alas! Lavoisier did not live long enough to dispel other misleading ideas in chemistry, but he paved the way for the triumph of the atomic theory.

The Atomic Theory of Matter.—Away back in the dawn of science the old Greek philosopher, Democritus, imagined the universe to be composed of infinitesimally small particles or atoms, differing in size, weight and shape, and held that these atoms were eternal, invisible and—as the word signifies—indivisible. This was not the only view held amongst the Greeks, for Xenophanes, who lived about the time of Pythagoras,

rather believed that matter was continuous, with no gaps between the particles. We need not discuss these ancient guesses at the structure of matter, nor the interesting speculations on the subject made by the Roman poet Lucretius and others, but come at once to the views on atoms put forward just after Lavoisier's death.

The Law of Definite Proportions.—Before considering more modern views on atoms, we must draw attention to four laws of chemistry that were established about this time by four different men, working independently in four different countries. The first of these men was Joseph Louis Proust, a French apothecary, who was born in 1755, and who, after a brilliant university career in Paris, became professor of chemistry in Madrid. Here he carried out most of his research work, until the Peninsular War brought about the destruction of his laboratory and all that it contained. His labours in the Spanish capital led to the establishment of the first of the four chemical laws to which we have referred.

Berthollet had argued that chemical compounds varied in character according to circumstances, and that the force inducing the union of elements acted somewhat in the same way as gravity—that is to say, that the affinity between any two bodies depended on their respective masses. It was thought, for instance, that a metal could unite with oxygen in gradually increasing proportions, and that the composition of the resulting substance was not immutable. Proust denied this, and said that an oxide of iron or of any other metal always had the same composition whether it occurred free in nature or was manufactured in the laboratory, and, further, that when the metal or non-metal united with oxygen to form two or more compounds, there was always a definite gap between any two successive oxides. To take a modern example, the oxides of nitrogen, nitrous oxide (N_2O), nitric oxide (NO), nitrogen trioxide (N_2O_3), nitrogen dioxide (N_2O_4 or NO_2), and nitrogen pentoxide (N_2O_5), Proust insisted that there could not be any compound intermediate between any two successive members of the series. This is known as the law of multiple proportions.

The next step, and the most fundamental, which follows

logically from Proust's law, was taken by John Dalton. Dalton's simple but revolutionary conception of combining weight was as follows: When one element united with another in more than one proportion, the weight ratios were some simple multiple of the lowest proportion. The combining weight of an element thus represented *the weight of the atom* of that element, relative to that of the atoms of other elements. Looking at the list of compounds of nitrogen and oxygen given on p. 181, it will be seen that two atoms of nitrogen unite with 1, 2, 3, 4, or 5 atoms of oxygen, but never with a fraction of a whole number. The law of multiple proportions is at once intelligible in terms of Dalton's atoms.

The Law of Combination of Gases.—The third law was established by a French chemist, Gay-Lussac, who was born in 1778 in Auvergne. After a somewhat exciting boyhood, spent during the troublous days of the French Revolution, Gay-Lussac became a teacher in the Paris Polytechnique. In a balloon ascent he collected samples of the atmosphere at various heights, up to nearly five miles, and found that the relative composition of dry air always remained constant. The law with which his name is primarily associated is that known as the law of volumes. Following on Cavendish's demonstration that two volumes of hydrogen always unite with one volume of oxygen in producing water, he went on to prove that two volumes of carbon monoxide (now written CO) unite with one volume of oxygen to form two volumes of carbon dioxide, now expressed $2CO+O_2=2CO_2$; that one volume of hydrogen and one of chlorine produce two volumes of hydrogen chloride,* and so on. In 1808, he announced his law —viz., that when gases combine they do so in volumes bearing a simple ratio to each other, and the product formed, if a gas, has a volume bearing a simple ratio to the original volumes.

Equal Volumes of Gases at the same Temperature and Pressure contain Equal Numbers of Molecules.—The fourth law was one established in 1811 by an Italian who rejoiced in a name of no less than ten words, but who, for short, is always known

* This is now written $H_2+Cl_2=2HCl$ (hydrogen chloride or hydrochloric acid gas), though not understood at the time.

as Avogadro. He was born in Turin in 1776, and for several years practised as a lawyer, although, at the same time, he was much interested in experimental science. In 1820 he became professor of physics in the University of Turin, and held that post until 1850, save during a period when, for political reasons, the chair was in abeyance. Into his other work we need not enter, but will confine ourselves to the law always known by his name.

The chemical formula for water is, as we have seen, H_2O; why should it not be $HO_{\frac{1}{2}}$? Because that would mean splitting an atom of oxygen, for O represents the smallest possible quantity of that element, just as H_2O represents the smallest possible quantity of water. To this unit of water Avogadro gave the name of "molecule."* A molecule of an element may consist of one or more atoms; thus a molecule of mercury is Hg, of oxygen

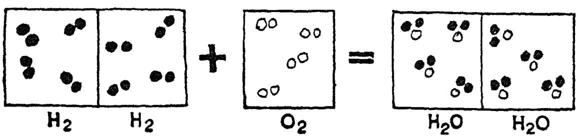

FIG. 83.—AVOGADRO'S LAW. (AFTER PARTINGTON.)

is O_2, of ozone O_3. Fig. 83 represents the union of hydrogen and oxygen to form water. If n represents any number, in the present instance 4, then since a molecule of hydrogen is composed of two atoms and a molecule of oxygen is also composed of two atoms, $4n$ atoms of hydrogen will unite with $2n$ atoms of oxygen to form $2n$ molecules of water. Now Avogadro's law states that at the same temperature and pressure equal volumes of these gases contain equal numbers of molecules. In the figure each square represents one volume, and there are two volumes of hydrogen, each containing four molecules of paired atoms, and one volume of oxygen containing four molecules of paired atoms, giving two volumes of water vapour, each containing four molecules of triple atoms. But this was not understood in 1811; until 1858 the formula for water was HO where O stood for a weight of 8.

* This was not understood at the time, and the lack of distinction between atom and molecule, for the smallest units of elements, caused dire confusion for nearly half a century.

Dalton's Atomic Theory.—Let us now consider the general atomic theory put forward by Dalton. John Dalton came of Quaker stock, settled near Cockermouth in Cumberland. He was born in 1766, and was the son of a weaver, who also farmed a small croft. At the age of fifteen he joined his brother in keeping a boarding school at Kendal, but the venture was not a financial success, so in 1793 he removed to Manchester to take up the duties of science lecturer in New College. After six years of this work he gave it up, and supported himself by private tuition. In later life he was granted a Civil List pension, and so was able to devote himself entirely to his favourite study, chemistry. He never married, but boarded with a clerical friend in Manchester for the last twenty-five years of his life. He died in 1844 at the age of seventy-eight.

As we have just seen, on the foundations of the Laws of Definite and Multiple Proportions, he based his "Atomic Theory." He started by assuming that every chemical element was composed of excessively minute particles or "atoms," possessing certain definite characters which never change, no matter how they may be compounded with other atoms. These atoms were, he held, incapable of division: "Thou knowest thou canst not cut an atom," he said. Every atom of an element is identical with every atom of the same element, but each separate element is composed of atoms of different weight. What was the weight of an atom? Exceedingly small, of course, but it must have some weight. Having no means of estimating such infinitesimal quantities, he took as unit weight the element hydrogen, the lightest known, while the combining weights of the atoms of other elements were regarded as multiples of unity—*i.e.*, atomic weights. Since Dalton erroneously supposed, on Avogadro's basis, that equal volumes of different gases contained the same number of *atoms*, if the weight of a volume of chlorine, combining with one volume of hydrogen, was thirty-five times that of the volume of hydrogen, then the atomic weight of chlorine was thirty-five. Similarly he determined the atomic weight of oxygen to be eight as compared with hydrogen. In modern chemistry we call these "equivalent weights," and proper atomic weights could not be

deduced till the true significance of Avogadro's hypothesis was grasped in 1858 (Cannizzaro). So water for many years was given the erroneous formula HO.

Hydrogen as the Primary Element—Prout's Hypothesis.—From the earliest times of which we have any record philosophers have always been striving to arrive at simple laws that would explain and govern many apparently disconnected facts, so when Dalton's atomic theory was made public, it was only natural that some chemists should begin to speculate as to the possibility of all the elements being made up of atoms of hydrogen. The first to put forward this view was William Prout, who was born at Horton in Gloucestershire in 1785, and ultimately graduated as a doctor of medicine of Edinburgh. After a study of Dalton's theory, he published a paper in 1815 in which he gave it as his opinion that the atomic weights of the various elements were all multiples of the lightest of them—viz., hydrogen—which he called the "protyle," from the Greek words *protos*, first, and *hule*, stuff. Thus all matter would be built up of this single primordial stuff, though the genesis of the elements remained unexplained. At first this rather alluring hypothesis "caught on," but when more accurate estimates of atomic weights came to be made, it was seen that they were by no means always whole numbers, and so the idea was gradually abandoned. It was revived in a new form many years afterwards, and as we shall find Prout was not far out.

Estimation of Atomic and Molecular Weights—Chemical Symbols.—Very important work in connection with atoms and molecules was carried out in the early years of the nineteenth century by the Swedish chemist Berzelius. He was the son of a schoolmaster in East Gothland, and was born in 1779. After a somewhat broken educational career, he took his medical degree at the University of Upsala in 1801, and ultimately became professor at the Military Academy at Stockholm. As this was the period when Dalton was publishing his atomic theory, Berzelius took a keen interest in the subject, and, with great labour, estimated the atomic and molecular weights of over 2,000 substances, and, in the course of doing so, discovered several new elements. We have a constant reminder

of him every time we write a chemical formula, for it is to him that we owe the chemical symbols for the elements in use today, so far as these elements were known in his day.

Sir Humphry Davy's Work on Chemistry.—Sir Humphry Davy was not only a great physicist but also a great chemist. Indeed, his first work in science was connected with the nature of the gases used in the Bristol Pneumatic Institute (p. 140), and his experiments included the inhalation of various gases, whose effects on the human body were quite unknown. In the course of his investigations he very often risked his life, for to breathe carbon dioxide, hydrogen, nitrogen, marsh gas and so on, was, to say the least of it, a very risky proceeding. Soon after his appointment to the Royal Institution, he began giving a course of lectures on agricultural chemistry, and continued doing so for several years. These lectures were published in 1813, and formed the most important textbook on the subject for the next fifty years. When he turned his attention to electricity he very soon, as we have seen, applied the method of electrolysis to the decomposition of substances like potash and soda, and isolated the metals potassium and sodium, so that these two alkalis turned out to be compounds and not elements. He next investigated what were called the "alkaline earths," baryta, strontia and lime, and found that they were oxides of three new metals, barium, strontium and calcium.

The Nature of Chlorine.—Scheele had found that when sulphuric acid, or "oil of vitriol," was poured on a mixture of black oxide of manganese and common salt, a greenish gas was given off. This gas when united with hydrogen formed what was called "spirit of salt" or muriatic acid, from *muria*, the Latin name for brine (it is formed when vitriol acts on salt alone and is now called hydrochloric acid). Lavoisier thought the green gas must be an acid, and therefore must contain oxygen. Scheele also tried to analyse it, but, beyond noticing that the gas bleached vegetable colouring matters, he could make nothing of it. Davy tried heating it with all sorts of substances, but never obtained any oxide, so he at last came to the conclusion that it must be an element, and gave it the name of "chlorine," from the Greek word *chloros*, green—the colour of the gas.

Davy thus added very materially to our knowledge of chemistry, for we must not forget that his invention of the safety lamp was based not only on his knowledge of physics but also on his knowledge of the chemical compounds, marsh gas, carbon dioxide and carbon monoxide, which played so important a part in his own invention.

Other great names in chemistry now begin to appear on the horizon, but as these are associated with the tremendous developments of modern times, we may leave them over for the moment and turn to the last of the five great sciences, biology.

§ v. Biology

Increase in Knowledge of Plants and Animals.—Ever since the days when Columbus, Vasco da Gama, Magellan and Cabot sailed into the unknown to find new lands, there had been hosts of travellers who had explored the newly discovered countries, or less ambitious persons who had wandered over regions nearer home, seeking to acquire knowledge of Nature and her productions. Many of these were students of natural history, who brought back with them new and strange plants and animals they had met with in their travels.

While the old Greek biologist, Theophrastus, knew at least 500 different kinds of plants, the herbalists of the fifteenth century described over 2,000, and these they arranged either alphabetically or in groups, according to what they called their " vertues "—*i.e.*, their uses to man in medicine or the arts. Still new forms flowed in, until in the seventeenth century over 10,000 kinds of plants were known. At the present moment we know of at least 400,000 species of plants, while the numbers in the animal world are greater still. The late Sir Arthur Shipley gives a total for the animal kingdom of 597,000, of which the insects alone account for no less than 470,000.

The problem before the botanist and zoologist was obviously to arrange all this mass of material into some sort of scheme, so that, when a new plant or animal was discovered, a place for it might be found.

Nomenclature of Plants and Animals.—In the early days a plant or an animal was not known, as it is now, by two names, but by short sentences describing some marked peculiarity it possessed. One of the first to recognise the clumsiness of this method was a German herbalist, called Kaspar Bauhin, who lived in the early years of the seventeenth century. He attempted to give plants two names only, one the generic or surname, the other the specific or christian name, and, as is the custom in a town directory, the surname came first—not John Smith, but Smith, John. Thus a buttercup was called *Ranunculus acris*, not *acris Ranunculus*, and other kinds of buttercups, differing in certain details, received specific names indicating the peculiarity in question—*e.g.*, hairy, *hirsutus*; aquatic, *aquaticus*; bulbous, *bulbosus*, etc. The names chosen were most commonly Latin, because Latin was the language used by the learned in those days, and every botanist, no matter what his nationality, could recognise the names of the plants in a language which was common to all nations.

Different genera were next seen to show still broader likenesses, and were grouped together in families, and these into yet larger divisions, such as those we found Ray created—viz., dicotyledons and monocotyledons. Precisely the same system of naming was adopted for animals. Of course, the early naturalists did not rename all plants and animals on this plan, but they made a beginning at it, and since then it has always been called the binomial system of nomenclature, and is now universally adopted.

CARL LINNÆUS.—Nearly a century after Bauhin's time, a much more famous man pressed on the reform, and carried it out in its entirety for both plants and animals; this was Carl Linnæus. Before attempting to estimate the services Linnæus rendered to biology, it will be well to know something of the life of this remarkable man.

Linnæus was born in 1707 at Råshult in Sweden, where his father was a pastor. It is not generally known that "Linnæus" was not his real name, but Ignomarsen; but owing to his father's house being overshadowed by a grove of lime or linden trees, the family came to be called Lindelius, which became

modified into Linnæus, and by that name he is always known. As is not unusually the case, the father's views as to his son's future did not find favour with Carl, for while the pastor wished his son to follow the clerical profession, Carl spent his time collecting natural history specimens. His school reports were so bad that his father gave up the idea of the ministry as a career for him, and arranged to apprentice him to a shoemaker! Fortunately the local doctor took an interest in the lad, and at his instigation Carl was sent to the University of Lund to study medicine. From there he went to Upsala, where he became assistant to the aged professor of botany, Rudbeck, after whom is named the small yellow sunflower so often cultivated in our gardens.

In 1732, when he was still an undergraduate, he went on an exploring and collecting expedition to Lapland, and on his return tried to support himself by teaching science. In this, however, he was unsuccessful, not because he had no pupils, but because he was, by regulations, disqualified from receiving payment for giving instruction without possessing a university degree. Without money he could not obtain a degree, and without a degree he could not even earn a living, so there seemed to be nothing left but to return to the cobbler's shop. But then a young lady came to the rescue. She was the daughter of a wealthy physician named Moraeus, but although the two young people had settled their future to their own satisfaction, the doctor intervened and refused his consent to their betrothal, let alone marriage, until Linnæus had taken his degree and set up in practice for himself. Then the girl showed her quality and her faith in her lover, for she handed over to Carl all her own money, which, added to his savings, enabled him to go to Holland, where, in due course, he graduated as doctor of medicine in the University of Harderwyk, at the age of twenty-eight.

But his period of service for his Swedish Rachel was not yet complete. Instead of hurrying home to put up his brass plate he went to Leyden, then a great seat of learning, and there he made the acquaintance of Boerhaave, the famous professor of medicine, who obtained for Linnæus the post of physician to the burgomaster of Amsterdam, who was himself a horticulturist of

some repute. The burgomaster sent Linnæus to England to obtain specimens for the Botanic Gardens at Amsterdam, and during his visit he met some of the leading scientific Englishmen of the day. It was about this time that he published the first of the long series of books for which he afterwards became so famous.

More than three years had passed since he had bidden farewell to his fiancée, and now that he was known as a scientific man of high standing, his future father-in-law withdrew all opposition to the wedding, and so at last he won his reward, and the lady was repaid for her trust and loyalty. After a short time spent in Stockholm, Linnæus was appointed to succeed Rudbeck in the University of Upsala, at the age of thirty-four, and was now free to devote himself to the science in which he had made his name known all over Europe. In 1749 he had over 100 students in his class, but that figure was soon greatly exceeded, for, mainly owing to the reputation he had acquired as a teacher, the number of students in the university rose from 500 to 1,500. In Upsala he remained for the rest of his life, dying there in 1778 at the age of seventy-one.

The "Systema Naturæ" and Binomial Nomenclature.—Let us now see in what respects Linnæus advanced the science of biology. When he went to Leyden he took with him a work on which he had been engaged for some years, and which he called the "Systema Naturæ," or general scheme of Nature. When first published in 1755 it comprised only twelve folio pages of printed matter, merely an outline of his ideas on how to arrange plants, animals and minerals. No less than twelve editions of the "Systema" were brought out during his lifetime, each one an extension of its predecessor. Zoologists, as a rule, take the tenth edition, of 1758, as their starting-point, while botanists prefer another work called the "Species Plantarum," published in 1753, as their guide to the naming of plants. The important point to remember is that, both in these and in other works which we need not mention, Linnæus brought into universal use the binomial method of naming plants and animals that had been suggested by Kaspar Bauhin more than a century before. In the mode of describing plants and animals Linnæus also made considerable improvements.

Instead of the long-winded descriptions of plants that the herbalists indulged in, he gave the essential characters in one short sentence in which there was not even a verb. Thus the wild rose, *Rosa canina*, was described as "the common rose of the woods with a flesh-coloured, sweet-smelling flower."

The Conception of Species.—Another feature of Linnæus's teaching was the emphasis he laid on the idea of a "species," but here he showed himself far behind John Ray. Before Ray's time the word "species" was used in the vaguest possible way, just as our modern newspapers talk of the "human species" or the "orchid species," although there is only one species of human being and something like 8,000 species of orchids. Ray, on the other hand, considered a species as all the individuals that have arisen from similar parents and that give rise to similar offspring. He noticed, however, that species were not always strictly constant; every now and then seedlings might grow into plants that differed considerably from their parents, and so he recognised the importance of variation. In the earlier editions of his work Linnæus insisted that species were constant and immutable. He held that in the beginning, when the world was first stocked with plants and animals, some 6,000 years ago, there was one pair of each kind of organism to start with, and that all the lions, tigers, dogs, daisies, roses, lilies and so on were the direct descendants of the original pairs of each that had been created. Indeed, he expressed this view quite dogmatically in a well-known and often quoted sentence: "There are never any new species; there are just as many species now as there were forms created by the Infinite Being in the beginning." Later on, he could not help seeing how common and how widespread variation really was, and in later editions of the "Systema" he does not express himself quite so positively on the matter.

Linnæus never studied the minute structure of either the plant or of the animal in the way that Grew and Malpighi did; he knew little or nothing of how the machine worked, in other words, of the subject of physiology—really the most important part of biology. Again, holding the views that he did on the constancy of species, he could not recognise the existence

of any genealogical relationship between them. What was left? Classification, but not the kind of classification we aim at nowadays, where we strive to group animals and plants in such a way as to show their probable ancestral origins, but a classification which was merely a catalogue arranged in divisions and subdivisions to facilitate the naming of some unknown organism.

The Sexual System in Plant Classification.—One of Linnæus's greatest achievements was his so-called "Sexual System" of classifying plants. As a matter of fact, the system was not sexual at all; sex did not actually come into the question, although the apparent organs of sex did. It may be as well to justify this statement. On examining any common flower, such as a buttercup (Fig. 84, A), it is easy to recognise outside, or lower down, five greenish leaves called sepals, S; these are followed by five yellow petals, P, and these again by numerous slender threads with club-shaped heads, the stamens, A, containing a yellow powder, the male fertilising material or pollen; and finally, in the centre, a number of ovoid green bodies called carpels, G, which contain ovules and are, therefore, regarded as female organs. In another flower (Fig. 84, B)—*e.g.*, of Enchanter's Nightshade—the same four kinds of structures may be distinguished, but there are only two of each, the pair of carpels (G) being joined together and sunk below the level of the other parts, though continued upwards as a slender stalk or style, ending in a knob-shaped head, called the stigma, G′.

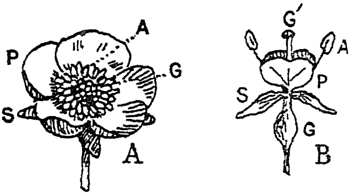

FIG. 84.—A, BUTTERCUP; B, ENCHANTER'S NIGHTSHADE.

In his "Sexual System" of classifying plants, Linnæus made great use of these parts of the flower, dividing them into groups, distinguished, first, by the number of stamens they had; and these groups he again split up according to the number of carpels, or rather styles, they possessed. Such a classification would be equivalent to that exhibited by a city directory where all the Smiths, Wilsons, or Robinsons are grouped together,

each group subdivided according to the christian names, quite irrespective of their real family relationships. Let us give him the credit, however, of realising that this plant directory was not a true system of classification, but only a makeshift, useful for cataloguing temporarily the thousands of plants that were already known, and the thousands more that were being discovered year by year. He himself warned his readers that his scheme was meant for convenience only, and to form a guide to the rapid naming of any particular plant. In later years he made an attempt—in his "Philosophia Botanica"—at drawing up a natural system based on real likeness in structure, taking all features into account, but this work he never completed.

It will thus be seen that, although Linnæus published an enormous amount of material and carried with him crowds of enthusiastic followers, it cannot be honestly said that he made any discoveries in biology comparable with those made by Davy or Faraday in physics, or by Lavoisier in chemistry. Indeed, one distinguished modern botanist, Professor Sachs of Würzburg, said of him that he showed "an utter incapacity for careful investigation of any subject at all difficult to observe." In these circumstances, it may, perhaps, be asked, if he contributed so little to the advancement of the science why mention him at all? For the same reason that Ptolemy's name is so important in the history of astronomy. He, too, produced a system, not of plants and animals, but of the universe, which was accepted by the learned of all nations for over a thousand years, and yet which was utterly erroneous. So, too, Linnæus put forward a classification of plants that became extinct before a hundred years had passed. But just as Ptolemy's mistaken ideas led Copernicus to write the "Revolution of the Celestial Bodies," so Linnæus's quite unnatural system was indirectly the cause of the birth of the natural system put forward by the French school of botanists some fifty years after his death.

There is no risk of his name being forgotten, for it lives in the title of the third great scientific club of natural historians in Britain, the "Linnean Society," at a meeting of which, a

century afterwards, the doctrine of the constancy of species on which Linnæus pinned his faith was completely overthrown by the greatest of all biologists—Charles Darwin.

General Aspects of Biology.—We may regard the science of biology from several aspects. First of all, we may consider plants and animals from the purely structural point of view, their external form or morphology, their internal constitution or anatomy with its corollary, histology—*i.e.*, the study of tissues—and on the knowledge we thus acquire we formulate schemes of classification. If our classification is to be in the true sense natural, it must take into account all parts of the organism, not merely one selected feature. Further, in formulating such a classification we must not neglect to take into account the representatives of the plant and animal worlds long since extinct, and now available only in the form of fossilised fragments.

No matter how detailed our knowledge of these subjects may be, we have not thereby acquired any adequate conception of the science of biology, which, as the name indicates, is the study of living things, while morphology, anatomy, and histology might more appropriately be termed necrology, a study of corpses, from the Greek word *nekros*, dead. It is not enough to analyse a complex machine at rest, we must also study it in motion, if we are to gain any real acquaintance with the uses of its various parts. This department of biological knowledge is termed physiology, the study of functions. A very casual glance at the living organism shows us that the functions of plant and animal alike may be grouped under three headings: first, those concerned with feeding or nutrition; second, those concerned with multiplication or reproduction; and, third, those concerned with response to stimuli or sensitivity.

There is yet another aspect of biological study, perhaps the most difficult of all—viz., that of origins. This is called phylogeny, from two Greek words meaning "lineage of the tribe." With these three departments of biology—morphology, physiology and phylogeny—biologists in Linnæus's time were most unequally acquainted. Linnæus himself had a good

knowledge of external morphology, but he does not seem to have used the microscope at all. He was in no sense a physiologist, and for him, with his belief in special creation and the constancy of species, phylogeny did not exist. In the years following Linnæus, the biological outlook broadened; physiology became of first-rate importance, and the dogma of the constancy of species began to give way to the doctrine of evolution.

CUVIER.—One of the first to break new ground, so far at least as the animal kingdom was concerned, was Georges Leopold Cuvier. His family were Protestant refugees from the region of the Jura, where Georges was born in 1769. He was destined for the clerical profession, but his keen interest in natural history soon led to his forsaking the study of theology. In 1788, owing to his family's reduced circumstances, he had to take up teaching, and became tutor to the son of a nobleman near Caen, where he remained for six years. Here he spent much of his time dissecting marine animals. Accounts of his doings reached the ears of the leading zoologists in Paris, and, as a consequence, he was invited to become an assistant in the Jardin des Plantes. He accepted the post, and ultimately became professor of comparative anatomy there! He afterwards rose to high rank in the State under Napoleon, and was created an Officer of the Legion of Honour in 1826, and a baron in 1831. He did not live long to enjoy his rank, for he died of paralysis in 1832.

Comparative Anatomy and Palæontology.—When we turn to Cuvier's work in biology, we find him in some respects quite as retrograde as Linnæus. In spite of the work of Redi-Leeuwenhoek, and others (p. 66), he believed firmly in spontaneous generation of life from inorganic or dead material. He thought that the fertilised egg contained within it the whole adult organism in miniature, and that development was merely an unfolding or expansion of its parts; also he was as staunch an upholder of the dogma of the constancy of species as Linnæus was himself. But he certainly opened up a new field that Linnæus had never explored, that of comparative anatomy. He published an important textbook on that subject, in which he dealt with the minute structure of both higher and lower

animals. Not content with studying living forms, he worked out the nature of the animals whose fossil bones were to be found plentifully in the neighbourhood of Paris, and from these fragments reconstructed the organisms as they might have appeared in past ages.

The Classification of Animals.—Cuvier's greatest work was "The Animal Kingdom arranged according to its Organisation," which was published in 1816. In this magnificent treatise he laid down the general principle that animals are built in one or other of four types: first, the Vertebrata, including all those that possess a bony skeleton with a backbone; second, the Mollusca, such as snails, limpets, mussels, etc., soft-bodied animals without an internal skeleton, but often with shells; third, Articulata, jointed animals like lobsters, worms and insects; and fourth, Radiata, or animals whose bodies were radially symmetrical, like starfish, sea anemones, polyps and such like.

Correlation and Adaptation.—Another of his doctrines was the "correlation of parts," meaning that every organism is a co-ordinate whole; if any part be changed in any way, every other part must change also. If, for instance, an animal possesses a stomach adapted to digest raw flesh, its teeth are suited to tear the flesh to pieces, its claws to seize and hold it, its senses to recognise the presence of its prey and its limbs to overtake it. Such animals he called Carnivora, but the various subtypes of carnivora have special peculiarities of their own, special kinds of teeth, claws, etc., fitted for distinct kinds of prey, and created to meet these ends.

Saint-Hilaire.—Geoffrey Saint-Hilaire was born in 1772, and died in 1844. He was at first a colleague of Cuvier at the Jardin des Plantes, but later became professor of zoology at the Museum of Natural History. In opposition to Cuvier, Saint-Hilaire insisted on the principle of homology—*i.e.*, he held that the organs of animals were not specially created to fulfil a definite purpose, but that when conditions were altered an organ carrying out another duty could be changed to suit the new circumstances. The controversy between these two distinguished zoologists marks the first rumblings of the storm

that broke out a few years later, when the whole subject was reopened by the publication of Lamarck's great work on " Animals without Vertebræ."

De Jussieu's Classification of Plants.—Returning to the plant world, we find that Linnæus's system of classification had been adopted not only in his own country, Sweden, but also in Germany and England; but perhaps the esteem, not to say reverence, in which that great naturalist was held, had as much to do with the general acceptance of his views as the inherent merits of the system itself. At all events, the "Sexual System" never caught on in France, where Ray's ideas were preferred. Ray's system was cordially received by Antoine L. de Jussieu, who made it the basis of his own scheme published in 1789. Antoine was the nephew of Bernard de Jussieu, the custodian of the Royal Gardens at Versailles, who had laid out the beds in the gardens in accordance with the views as to relationship expressed by Ray. He never published anything himself, so that we may assume that his nephew's books embody any original views he held.

De Jussieu's treatise was called the "Genera of Plants," and in it we find an extension of Ray's " Method," which he adopts and expands. He divides plants into Dicotyledons, Monocotyledons, and Acotyledons, the last group including all the lower plants, such as ferns, mosses, fungi, seaweeds, etc. In his classification of flowering plants de Jussieu makes a great point of the position of the stamens and petals in their relation to the carpels, speaking of them as "hypogynous" when they arise below the level of the carpels, " perigynous " when they spring out round them, and " epigynous " when the carpels are entirely beneath the stamens and petals (Fig. 85). This was a most unfortunate feature to select, for if he had only traced the

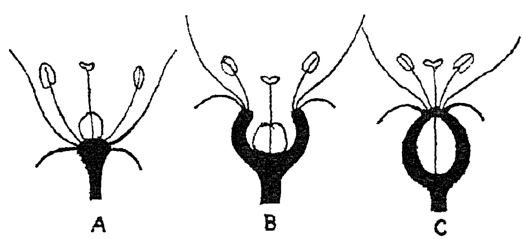

FIG. 85.—A, HYPOGYNY; B, PERIGYNY; C, EPIGYNY.

development of the flowers of some of the Saxifrages, he would have seen that in this family there were cases where the flower started by being hypogynous, passed through a perigynous condition and ended in being epigynous. It was the old mistake that Linnæus made of basing a classification on one character only.

PYRAME DE CANDOLLE.—The next important step was taken by two members of a very distinguished family of botanists, that of de Candolle. The first of these was Augustin Pyrame de Candolle, who was born in Geneva in 1778. After studying in the university in that city, he went to Paris, where he made the acquaintance of Cuvier, Saint-Hilaire and the other naturalists who had their headquarters at the Jardin des Plantes and the Museum of Natural History. After spending ten years in Paris he became professor of botany at Montpellier, but after another decade he returned to Geneva to hold a similar post in its university. While he was at Montpellier he published a very important little book, which in its general character recalls Lavoisier's "Elementary Treatise on Chemistry," because it laid down the fundamental principles of the subject as they shaped themselves in de Candolle's mind. He called the book an "Elementary Theory of Botany." It was published in 1813, and was the first textbook on the science.

The Doctrine of Symmetry.—The chief thesis de Candolle sets out to establish is that the foundation of classification is form and structure, and that physiology is of no value as a guide to relationship, indeed, that it is often misleading. He then expounds what he calls the symmetry of organs. To understand this doctrine requires the study and comparison of a large number of forms, from which it can be seen that the fundamental symmetry becomes obscured by three causes: degeneration of parts, abortion of parts and adherence of parts of one kind to parts of another. Thus the flower of the snapdragon (Fig. 86) has only four stamens and two carpels, while, in accordance with the doctrine of symmetry, it ought to have five stamens and five carpels. One stamen, X, is entirely

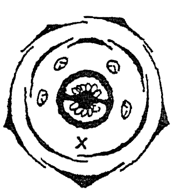

FIG. 86.—SNAPDRAGON.

absent, but in figwort there is a scale where the missing stamen ought to be—*i.e.*, the fifth stamen has degenerated in the figwort and aborted in the snapdragon.

The adherence of parts is a frequent feature in flowers. In the flower of the orchid, for example (Fig. 87), which is built on the trimerous plan—*i.e.*, with parts in threes—there is only one stamen, and that is fused to the style. "The whole art of classification," de Candolle says, "consists in discovering the plan of symmetry."

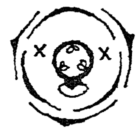

FIG. 87.—ORCHID.

Notwithstanding that he held such views, it is strange that he was at the same time an upholder of the dogma of the constancy of species. If a flower possesses four functional stamens and one degenerate one, when, according to the doctrine of symmetry, it ought to have five perfect stamens, it must either have been created with this useless vestige of a stamen, and then there could not have been any degeneration, or it must have been derived from some ancestral type with five functional stamens, and then there could be no constancy.

The Prodromus.—The classification of plants put forward by de Candolle, though an improvement on that of de Jussieu, was still very imperfect from our modern standpoint, but it served as a protest against the purely artificial schemes that followed the lines laid down by Linnæus, and it also formed the basis of the arrangement adopted in some form or another in many of the floras of today.

In addition to his efforts at establishing a "Natural Classification," as it is called, de Candolle began an immense work, "The Prodromus," or Outline of the Plant Kingdom, continued by his son Alphonse, with the aid of several other botanists. Begun in 1824, it was not completed until 1873, when it comprised seventeen volumes of over 12,000 pages. It professed to be an account of every known flowering plant, arranged according to de Candolle's scheme; but as our views on the relationships of the higher plants underwent enormous changes after the middle of the nineteenth century, it is now regarded as a work of reference only.

Bentham's "Genera Plantarum."—One of the botanists who aided Alphonse de Candolle in completing his father's work was George Bentham. He was born in 1800 at Stoke near Portsmouth, and in his earlier years studied law and philosophy. In 1830 he made the acquaintance of Alphonse de Candolle, and began contributing to the great Prodromus, giving up law as a profession altogether. He travelled extensively, making collections which he ultimately presented to the Herbarium at Kew. Almost any day he was to be found there, working quietly and systematically at the description of flowering plants. He became very friendly with Joseph Dalton Hooker, the son of Sir William Hooker, who was at that time Director of Kew Gardens, and was induced to take part in the preparation of a series of floras of the British Colonies, which had for some time been contemplated by the Kew authorities. While engaged on these labours, Bentham constantly found himself in difficulties with the limits of genera in the vegetable kingdom, and he soon realised that what was most needed at the moment was a clear statement as to the precise characters that constituted a genus. This led him to plan out his greatest work, the "Genera Plantarum," in the compilation of which he had the assistance of young Hooker. The general idea was to settle the limits of genera first and allow the grouping of these to suggest themselves naturally, instead of plotting out a scheme in the first instance and forcing the genera into it. The "Genera Plantarum" appeared at intervals between 1865 and 1883, and is still regarded as the standard work on the subject.

We need not discuss the classification scheme that resulted, beyond saying that it was a modification and extension of that of de Candolle; what is more important for us to notice is that throughout the entire work there is no reference to the lower plants; it follows the old plan of dealing with flowering plants only, and ignores the very existence of the host of non-flowering forms that, even in the first half of the nineteenth century, were beginning to receive attention from botanists. But a more remarkable point still is that no reference is made to the doctrine of evolution which, after the middle of the century,

began to leaven all the writings of biologists. Bentham was a firm believer in the dogma of the constancy of species, and although, towards the end of his life, he felt himself driven to accept the new views, his conversion came too late to make it possible to alter the plan of the "Genera."

The British Flora.—To Bentham we also owe the "Handbook of the British Flora," a book which, to this day, is the standard guide to the naming of our native plants. It is a work that is highly valued by every field botanist and constantly referred to, and yet Bentham tells us that he "amused himself by writing it before breakfast."

Plant Anatomy.—While de Jussieu, de Candolle, Bentham, and Hooker were thus elaborating classifications of flowering plants on what was called the "Natural System," there were many who devoted themselves to the microscopic study of plants, and who attempted to work out the structure of the various tissues and the way in which they were combined in the organism. The microscope was as yet a very inferior instrument when compared with what is now in use; indeed, one marvels how these early microscopists managed to make out so much with an instrument the modern student would despise.

It will be remembered that Robert Hooke, in 1665 (p. 64), had opened up the way to an understanding of the architecture of the organism by his discovery of the "cell"; but he and his successors, like Grew and Malpighi, confined their attention to the very obvious walls of the cells, and never enquired into the nature of the cell contents, which were lumped together as "sap," "vital juice," or "slime." It was not until 1812 that the anatomy of plants was placed on a new footing by the work of a German botanist called Moldenhawer, who was born in Hamburg in 1766, and ultimately became professor of botany at Kiel. He was the first to introduce the method of maceration or separation of the tissue elements by their prolonged immersion in water to which some acid had been added. By this means he was able to show that each cell and fibre had a wall of its own, and that they were not merely cavities in a homogeneous matrix, like bubbles in a foam. These cells were united in various ways to form different kinds of tissue, storage,

conductive, protective and so on, while these tissues in turn were grouped together in layers and strands to form roots, stems and leaves, etc.

Animal Anatomy.—On the zoological side also there were many who were using the microscope to discover the nature of the building materials of the animal body, and one of the most prominent of these investigators was Bichât, a French surgeon, who was born in 1771. Hitherto the anatomist had been content to analyse the animal body into organs, stomach, intestines, lung, heart, kidney and so on—but Bichât went deeper and analysed these organs in turn into tissues—muscular, nervous, glandular, etc. The next step was a reconsideration of the elements out of which the tissues were made, and the nature of the substances that were found in them.

ROBERT BROWN.—The first important advance on these lines was made by Robert Brown, the son of a Scottish clergyman in Montrose. He was destined for the medical profession, but devoted his leisure moments to the study of the plants of his native land. After a period spent as a medical officer in the army, he went on a surveying expedition to the Antipodes, where he spent four years studying and collecting examples of the then almost unknown flora of Australia and Tasmania. On his return to England he became librarian to the Linnean Society, where he had access to Linnæus's great herbarium. During the next five years he published several papers on the structure of the various groups characteristic of the Australian vegetation, and compared the flora with that of South Africa, South America and other regions of the southern hemisphere, and so laid the foundations of botanical geography, a subject greatly extended by Sir Joseph Hooker many years later.

The Structure of the Seed.—In these monographs Brown announced many discoveries in plant morphology and anatomy which are now commonplaces in all the textbooks. For example, he worked out the structure of the ovule and the seed, and showed that those of the pine, larch, fir and their allies differed from those of the ordinary flowering plant in being exposed on open scales or carpels, while those of the flowering plant were enclosed or hidden. Hence he was led to separate

plants of the pine alliance from all others, as "Gymnosperms"—*i.e.*, naked seeded—from ordinary flowering plants, which he named "Angiosperms"—*i.e.*, hidden seeded. He also studied the structure of the fertilising dust or pollen, and showed how pollen grains germinated on the stigma of the carpel and formed pollen tubes, which bored their way into the ovule and so brought about fertilisation.

Brownian Movement.—While investigating the passage of the contents of pollen tube into the ovule, Brown noted that the granules in the tube were in constant tremulous motion, a phenomenon common to all minute particles floating in a liquid. Brown offered no explanation of this peculiar motion, known since his time as "Brownian Movement," but in recent years interpreted as due to the bombardment of such particles by the molecules of the medium in which they are suspended.

Discovery of the Cell Nucleus.—In one of his papers dealing with the curious flowers of orchids he made a discovery which led to the foundation of a new section of histology—Cytology, or the study of the structure of the cell. In the superficial layer, or epidermis, of the leaf he noticed that each of the cells of which it was composed contained a definite granule or "nucleus," and further research convinced him that this body was present in all living cells (Fig. 88). We now know that the nucleus is a structure of supreme importance both in the plant and in the animal; that it governs the growth and division of the cell, and is the bearer of hereditary characters from parent to offspring. Papers and books innumerable have been written on the nucleus and its behaviour during cell growth and division, enough indeed to form a library in themselves; and some universities have gone the length of creating special professorships of Cytology; and all this has developed out of Brown's quite incidental observations on the leaves of some Orchidaceæ.

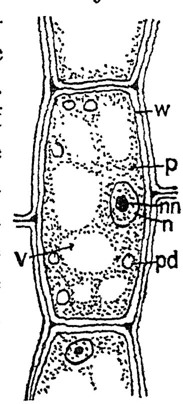

FIG. 88.—VEGETABLE CELL. w, wall; p, protoplasm; n, nucleus; nn, nucleolus; pd, plastid; v, vacuole.

There is scarcely a single department of botany on which

Brown did not leave his mark. The distinguished American botanist, Asa Gray, said of him, "Perhaps no naturalist ever taught so much in writing so little, or made so few statements that had to be recalled or even recast," and the great naturalist and traveller, Von Humboldt, conferred on Brown a title so well merited that it was unanimously confirmed by all his fellow-botanists: "Easily the first of all botanists, the glory and ornament of Britain."

Discovery of Protoplasm.—After the discovery of the nucleus by Robert Brown, several workers began to study the other contents of the cell, and it was not long before the general "sap," "slime," or "vital juice" that the earlier anatomists had noted as more or less filling the cell, and in which the nucleus lay, was found invariably to contain nitrogen. The same chemical discovery was also made in animal cells, where a nucleus was also found to be universally present. In the animal the cell-wall was observed to be not nearly so prominent a feature as in the plant, so that it began to dawn on men's minds that perhaps the contents were the most important things in the cell, and that the wall was of secondary value. To the nitrogenous contents of the cell the French anatomist Dujardin gave the name "sarcode" or "flesh," and showed it to be the real basis of the cell, the wall being merely an excretion from it. At length, in 1844, the German botanist, von Mohl, announced that, in his opinion, the "slime" of the plant cell and the "sarcode" of the animal cell were identical, and proposed the name "protoplasm" or "the first formed substance" to cover both, a name now universally accepted. Several years later the distinguished zoologist, Huxley, defined protoplasm as "the physical basis of life," for it is to its activities that all the wonderful phenomena are due that we sum up under the term "life." It has been analysed hundreds of times, and although we are able to say that it consists of at least half a dozen chemical elements, combined in an almost infinite variety of ways, and linked together somehow to make a complex and everchanging whole, we are as yet entirely ignorant how a particle of this mysterious substance is able to manifest all the remarkable changes which we associate

with the functions of nutrition, sensitivity and reproduction. The protoplasm of a plant ovum presents the same chemical characters as those of an animal ovum: the two protoplasms look the same under the highest powers of our best microscopes, and yet one gives rise to a forest tree, the other, perhaps, to a human being. Here we might truly say we meet with the supreme "riddle of the universe." When, if ever, we learn exactly how the constituent units of the protoplasmic framework are linked together, and what are the multifarious changes taking place in it, then, perhaps, we may learn how to make it in the laboratory. Even so we would not have created life.

The Cell Theory.—Another important question that occupied the attention of both zoologists and botanists of the middle years of last century was the mode of origin of the varied types of cell found in the plant and animal body, and the result of their investigations was the establishment of a doctrine known as the "Cell Theory." This doctrine, which was worked out chiefly by two German biologists—Schleiden, a botanist, and Schwann, a zoologist—might be expressed by saying that all tissue elements, no matter what their ultimate forms and functions may be, are derived from primary cells, uniform in appearance and structure, and all of these in turn from a fertilised egg cell. Every cell arises from a preexisting cell; "Omnis cellula e cellula" is a formula which reminds one of Harvey's famous aphorism, "Omne vivum ex ovo," every living thing comes from an egg.

Foundation of Cryptogamic Botany.—When we were considering the growth of the idea of a natural classification of plants, we had occasion to note that all the lower forms of vegetable life were practically ignored, for during the closing years of the eighteenth and the early years of the nineteenth centuries very little was known either of the structure or the life-histories of the hosts of organisms represented by ferns, mosses, seaweeds and fungi. By the middle of the nineteenth century, however, several botanists began to enquire into the nature of the Cryptogamia, or flowerless plants, and a considerable amount of information was slowly accumulated with regard to them. As, however, our knowledge of these organisms

is a product of the work done during the latter half of the century, we may leave that subject over for the present.

Foundation of Palæophytology.—In another department of botany also considerable progress was made during the early years of the nineteenth century, due largely to the labours of Adolphe Brongniart, who, in 1828, did for the vegetable kingdom what Cuvier had done for the animal. He examined with great care and skill the fossilised remains of the vegetation of past ages, accounts of which he published in a long series of monographs entitled " A History of Fossil Plants." Brongniart was born in 1801, and became professor at the Jardin des Plantes. He divided the whole geological series of strata into four epochs, each characterised by the dominance of certain types, but although more recent research has shown that his generalisations cannot be maintained, his detailed work is still regarded as classical.

Pioneer Work in Photosynthesis.—It will be remembered that, in 1774, Priestley wrote a book called " Experiments and Observations on Different Kinds of Air " (p. 169). In this he speaks of " the restoration of air, in which a candle has burnt out, by vegetation." He describes how a friend of his told him that while he was waiting for a boat to convey him to the Continent, he observed, at his inn at Harwich, a horse trough which the landlord refused to have cleaned out, because he found that the water remained longer sweet when the sides and bottom of the trough were " covered by a green substance which is known to be of a vegetable nature." After describing the " spontaneous emission of dephlogisticated air (oxygen) from water containing a vegetative green matter," he says he never found the emission took place save when the water was exposed to light.

Ingenhousz on the Gaseous Exchange between Plants and Air.—In 1730 there was born at Breda, in Holland, Jean Ingenhousz, who, after completing his university curriculum, began the practice of medicine first in Holland and afterwards, about 1764, in England. Four years later he became physician to the Emperor of Austria and resided in Vienna. His tastes seem to have been scientific rather than medical, for, during

his life in the Austrian capital, he began to send papers to the Royal Society of London, of which he was elected a Fellow on his return to England in 1778. In 1779 Ingenhousz published his "Experiments on Vegetables," carried out in his garden near London.

In 1796 he published another work entitled "On the Nutrition of Plants and the Fruitfulness of the Earth," in which he shows he had acquired a thorough grasp of the new chemistry founded by Lavoisier, a knowledge he confesses he did not possess when he wrote the "Experiments." He knew now that carbon dioxide was a compound of carbon and oxygen, and this enabled him to realise the significance of the gaseous interchanges taking place between the green leaf and the air in sunlight. His new interpretation of the phenomena is that the leafy shoots give off oxygen in light and carbon dioxide in darkness, while non-green parts emit carbon dioxide both in the light and in the dark. From the carbon and the oxygen the plant constructs "acids, oils, mucilage, etc.," and these substances are then combined with the nitrogen of the air. This latter idea is of course quite erroneous, but it took another fifty years to prove it so. That unfortunately was not the only blunder he made. Although he admitted that leaves absorb carbon dioxide from the air, he thought that a considerable amount also was obtained by the roots from the soil. Modern plant physiology teaches that all the carbon required by the ordinary green plant comes from the carbon dioxide present in very small quantities in the atmosphere, and the nitrogen from salts of nitric acid and ammonia in the soil.

De Saussure.—Nicholas Theodore de Saussure was the son of the celebrated naturalist, geologist and alpine explorer whom we have already mentioned as one of the pioneers in the science of geology. Theodore was born at Geneva in 1767, and was educated privately by his father. He studied medicine, mineralogy and natural history, and acquired a keen interest in chemistry from reading the works of Lavoisier. While still a lad he accompanied his father on his geological excursions, and learned from him habits of accurate observation of natural

phenomena, an accomplishment rare enough in those days. When his father made his historic ascent of Mont Blanc in 1787, he left his son at Chamonix, where Theodore employed himself in making meteorological observations, which afterwards proved of great value. In the following year father and son spent more than a fortnight on the Col du Géant, at an altitude of over 10,000 feet, and would have remained longer had it not been that their guides, alarmed at the threatening condition of the weather, compelled the two scientists to descend by the simple, though drastic, method of destroying all the reserve stores of provisions. While the father studied the geology and meteorology of the Col and its surroundings, the son devoted himself to the determination of the exact altitude of the camp, the height of the neighbouring peaks, and the density of the air. Theodore next travelled in England and Scotland, making observations and laying the basis of his future work in vegetable physiology. In addition to researches on plant nutrition, he gave much time to problems in organic chemistry, such as the composition of ether and alcohol, and the nature and properties of various oils. He also took part in many public affairs, and was for several years a member of the Council of the Republic. Although appointed to the chair of mineralogy and geology in the Academy of Geneva in 1802, nothing could induce him to give a course of lectures. After a singularly uneventful life he died in Geneva in 1845.

The Chemistry of Plant Nutrition.—De Saussure's chief work was undoubtedly his "Chemical Researches on Vegetation," a treatise published in 1804. In this book he proved that the seeds of plants will not germinate in the absence of air or oxygen, and that carbon dioxide retards germination owing to its poisonous effects on the tissues. He held that light had no effect on germinating seeds until green leaves appeared, and showed that a moderate addition of carbon dioxide to that normally present in the atmosphere favoured growth, provided that the intensity of light was increased correspondingly. He also showed that all green parts absorbed oxygen by night and restored it to the air by day, and by both

qualitative and quantitative methods, physical and chemical, he determined which of the constituents of the plant were derived from the air and which from the soil. He claimed that plants obtained all their carbon from the carbon dioxide in the air, and none from the soil, as Ingenhousz thought. He was quite familiar with the importance of the green pigment, chlorophyll, but he fell into the error of believing that other colouring matters could act in its place. Thus he experimented with plants that had red or purple foliage, like orache or the copper beech, and observed that such plants gave off oxygen in sunlight, and he jumped to the conclusion that the green pigment was not essential to carbon assimilation, *i.e.* photosynthesis, not noticing that chlorophyll was actually present though masked by coloured cell sap.

De Saussure drew attention to the fact that in the daytime a plant reassimilates all the carbon dioxide it has formed in the process of respiration, and hence that respiration cannot be demonstrated while photosynthesis is going on. This explains what puzzled Mayow in 1674, when he found that green plants were not killed by being placed under bell-jars, although animals were. While Ingenhousz regarded water merely as a vehicle for the transport of salts from the soil to the leaves, de Saussure showed that water was decomposed by the leaves in sunlight along with the carbon dioxide. Growth without respiration, he said, was impossible; all the minerals taken up in solution by the roots had their parts to play in the plant economy, and, by means of a long series of what might be termed balance sheets, he arrived at a tolerably clear idea as to which minerals were essential, and how much of each was necessary for healthy nutrition. He made out one very important point—viz., that the plant derives all its nitrogen from the soil in the form of nitrates and compounds of ammonia, and none from the vast supplies in the air. He went astray, however, in regarding animal and plant waste as the source of these salts, and thus started what was called the "humus theory," disproved towards the middle of the nineteenth century by the chemist Liebig. Lastly, de Saussure drew attention to the extreme dilution of the solution of salts taken

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in by the roots, and hence the necessity for the evaporation of the surplus water from the leaves—transpiration, as it is called nowadays.

From this summary of de Saussure's work it will be seen that the publication of his "Chemical Researches on Vegetation" constitutes a landmark in the history of Botany, and really forms the basis of almost all the work undertaken in plant nutrition up, at least, to the later years of the nineteenth century.

Sensitivity in Plants.—Another outstanding feature of the period was the publication of certain researches by a Hertfordshire horticulturist named Thomas Andrew Knight. Towards the close of the seventeenth century, Malpighi and others had observed the periodic movements of the leaves of some members of the pea family (Leguminosæ), and Linnæus and others had noted the responses given by the so-called "sensitive plant" as well as the curvings and twinings of tendrils and of stems like those of the hop and convolvulus, but in all cases these movements were ascribed to physical causes or to some mysterious "vital force."

Knight reopened the subject in a communication made to the Royal Society in 1806. He discussed the persistent movement of the roots of seedlings towards the soil and of the shoots away from it, no matter how he disposed the seedlings in the first instance. By fixing seedlings on the rim of a rapidly rotating wheel (Fig. 89, A) he found that, if the wheel was horizontal, the roots bent downwards and the shoots upwards at angles divergent from the horizontal, which depended on the speed at which the wheel was rotating, while if the wheel was vertical

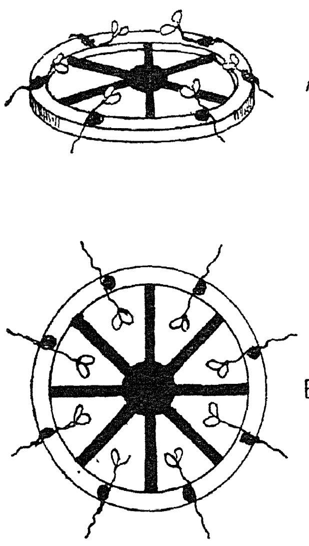


FIG. 89.—KNIGHT'S WHEEL.

(Fig. 89, B) all the shoots bent towards the nave of the wheel and the roots away from it. Knight's wheel was the forerunner of the instrument called a "Klinostat," now constantly used in every botanical laboratory. Knight tried to explain these movements by referring them to alterations in the position of the sap, but the explanation was by no means convincing.

He also noticed that roots grew towards water even in opposition to gravity, and that dorsi-ventral leaves always tried to place their upper surfaces at right angles to the path of the sun's rays. "I will request your attention," he says, "to the power of moving in the vine-leaf, on which I have made many experiments. It is well known that this organ always places itself so that the light falls upon its upper surface, and that if moved from that position it will immediately endeavour to regain it; but the extent of the efforts it will make, I have not anywhere seen noticed. I have frequently placed the leaf of a vine in such a position that the sun has shone strongly on its under surface; and I have afterwards put obstacles in its way on whichever side it attempted to escape. In this position the leaf has tried almost every method possible to turn its proper surface to the light." These words at once suggest a conscious effort on the part of the leaf to do something it was prevented from doing by some external agency. It is rather remarkable that Knight did not attribute to the leaf the power of perception or "feeling" so clearly indicated by the very words he uses to express the leaf's activities. "I am wholly unable to trace the existence of anything like sensation or intellect in plants," he writes; "I cannot conceive how the contortions of its stalk, in every direction, can be accounted for without admitting not only that the leaf possesses an intrinsic power of moving, but that it also possesses some vehicle of irritation." Of course, "the vehicle of irritation" was there in the shape of protoplasm, but, as we have seen, that mysterious substance was not recognised as the basis of any such sensory phenomena until many years afterwards.

Sensitivity in Animals.—Sensitivity in plants suggests sensitivity in animals, and that introduces us to a man whose achievements have scarcely received the attention they deserve.

Sir Charles Bell, as he ultimately became, was born in Edinburgh in 1774, the son of a clergyman of the Episcopal Church of Scotland. After a brilliant career in Edinburgh, he went to London in 1804 and lectured on anatomy and surgery. In 1811 he published his "Anatomy of the Brain," and in that work, as also in subsequent papers on the nervous system, he proved the presence of sensory nerve filaments carrying impressions from the terminal sense organs to the brain, and motor nerve filaments passing from the brain to the muscles, etc. (Fig. 90).

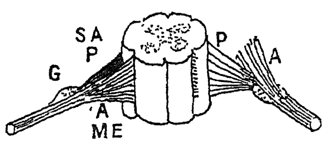


FIG. 90.—SPINAL NERVES.

These two sets of nerves are connected with the spinal cord by posterior and anterior branches, the former being sensory or afferent, and the latter motor or efferent. These and other researches on the nervous system brought him high honours, and his discoveries have been described as the greatest that had been made in animal physiology since Harvey demonstrated the circulation of the blood. He died suddenly in 1842.

The Dogmas of Special Creation and Constancy of Species.—When we were considering the works of Linnæus, de Jussieu, de Candolle, Cuvier and others, we noted that they all firmly believed in the constancy of species, although vague doubts seemed to have been present in their minds as to whether some degree of variation ought not to be conceded within the limits of the species itself. Holding such views, the classifications they formulated could not, of course, be anything but linear arrangements of plants and animals, for a genealogical or phylogenetic tree was impossible.

The first to call in question the special creation and specific constancy dogmas, at least in comparatively modern times, was Jean Baptiste de Monet, commonly known as the Chevalier de Lamarck. He was born at Bazentin in Picardy in 1744, and, unlike his elder brothers, who adopted the army as their profession, he was destined for the Church. In consequence of this decision he became a pupil in the Jesuits' College at Amiens, where, however, he developed a pronounced distaste for theology

and took the earliest opportunity of absconding and joining the army, then engaged in the Seven Years' War. As he arrived at camp, mounted on a derelict nag that he had acquired somehow, he was made a non-commissioned officer. His company suffered so severely in his first battle that Lamarck found himself, a lad of seventeen, in command of all that was left of it. But he showed the courage and determination that distinguished him throughout his whole career, for he resolutely refused to retire though facing great odds, until he had received definite orders from headquarters to do so.

Invalided from the army owing to an accident, he went to Paris to study medicine, but from the beginning showed himself particularly attracted to botany. The fruit of five years' unremitting labour, carried out under poverty-stricken conditions and without any patronage or even encouragement, was his "Flora of France," published in 1778. This work brought him to the notice of the Academy of Sciences, and after a short tenure of a subordinate post connected with that body, he was selected by Buffon as tutor to his sons. After two years of this life he returned to Paris, and was made keeper of the herbarium of the Royal Gardens, and finally professor in the renamed Jardin des Plantes. In 1794 Lamarck transferred his affections from botany to zoology, and immediately proceeded to reorganise the classification of the lower animals, which up till then had received the minimum of attention from zoologists, just as the cryptogams had been neglected by the botanists. He published his results in 1815 and 1822 in his splendid work "The Natural History of Animals without Vertebræ." Meanwhile he had become totally blind, and might have collapsed altogether had it not been for the devotion of his daughter, Cornélie, who was his constant helper and sympathiser, while the outside world treated him with indifference. Her prediction as to her father's future greatness came true in later years—"La postérité vous honorera." Lamarck died in 1829.

The Doctrine of Use and Disuse.—We need not do more than mention his views on the origin of life, for they were tinctured with an undoubted bias towards a belief in spon-

taneous generation, but will turn to his theory of evolution, which, although vigorously combated and even ridiculed, was the first serious attempt to overthrow the dogmas of special creation and the constancy of species. His general theory is given in the introduction to his "Natural History," and very briefly is that: variation is explicable on the ground of use and disuse; the constant use of an organ tends to its development and its disuse to its degeneration and ultimate abortion; every alteration in an organism so arising is passed on to its offspring, either to be maintained by it or to be allowed to fall into abeyance; acquired characters are inherited.

Whatever else may be said for or against Lamarck's theory, we must give him the credit of recognising the two fundamental factors that every evolutionist must take into account, however he may explain them—viz., the phenomena of variation and the phenomena of heredity.

To Lamarck also we owe the introduction of the word "biology," to signify the science which deals with living organisms, whether they be plants or animals.

CHARLES DARWIN.—The year 1859 was destined to be a fateful one not only for biology but for every department of learning, for in that year was published a book that has had a deeper and more far-reaching influence on the trend of human thought than any other that has ever come from the Press. That book was the "Origin of Species," by Charles Darwin. Its only competitor is the "Principia" of Sir Isaac Newton, and he and Darwin may rank together as the two greatest scientific men that the world has ever seen.

Charles Robert Darwin was born in 1809, at Shrewsbury, where his father was a well-known medical man. It is rather amusing to read how Darwin's early teachers looked on him as not far removed from a dunce! These were the days when higher education was considered as synonymous with an intimate knowledge of the classics, and it is on record that his headmaster on one occasion publicly reprimanded him for "wasting his time on such a contemptible subject as chemistry." "The school as a means of education to me was simply a blank," he writes himself. He does not appear to have been much more

of a success at college. At Edinburgh, where he went to study medicine, he found the professors "intolerably dull," and speaks of some of the lectures as "fearful to remember." As Huxley puts it: "The climax seems to have been attained by the professors of geology and zoology, whose prelections were so incredibly dull that they produced in their hearer the somewhat rash determination never to read a book on geology or in any way to study the science so long as he lived." This, be it remembered, was the decision of the future author of the "Structure and Distribution of Coral Reefs," and of the "Geological Observations on Volcanic Islands"!

Finding himself not likely to become a successful physician, Darwin exchanged Edinburgh for Cambridge, where he entered Christ's College with the view of reading for the Church; but he had no better word to say for Cambridge than he had for Modern Athens. "During the three years which I spent at Cambridge," he writes, "my time was wasted, as far as academic studies were concerned, as completely as at Edinburgh and as at school." If he passed the door of the geology lecture-room with a shudder, he found his way into the botanical one, and there he made the acquaintance of Henslow, "a man of rare character and singularly extensive acquirement in all branches of natural history." This acquaintance ripened into a friendship which lasted till Henslow's death in 1861. Henslow overcame Darwin's prejudice against geology, and succeeded in introducing him to Sedgwick, at that time professor of geology at Cambridge, and Darwin had to forswear his vow never to study the science again, for he not only accompanied the professor on his geological excursions, but set himself to master Lyell's "Principles of Geology," a work to which, in after years, he professed himself as fundamentally indebted.

Henslow was, however, responsible for more than merely turning Darwin's thoughts to botany and zoology; he showed himself possessed of a far-seeing vision that was the means of dedicating to science the man who was destined to become the greatest of her high priests. For it was due to Henslow that Darwin, when scarcely out of his teens, was appointed naturalist on H.M.S. *Beagle*, just about to start on a five years'

surveying voyage round the world. Thus another educational experiment was to be tried, and Nature herself was to take him in hand. This last attempt at instructing the future naturalist was as successful as the others had been futile, and was, as Darwin himself says, the starting-point of his second life.

The Theory of Evolution.—In a letter written in 1877, Darwin says, "When I was on board the *Beagle* I believed in the permanence of species, but, as far as I can remember, vague doubts occasionally flitted across my mind. On my return home in the autumn of 1837, I immediately began to prepare my journal for publication, and then saw how many facts indicated the common descent of species, so that in July, 1837, I opened a notebook to record any facts which might bear on the question. But I did not become convinced that species were mutable until, I think, two or three years had elapsed."

Soon after his return from his travels, Darwin came across a book called "An Essay on the Principles of Population," written by the Rev. Thomas Malthus, a Surrey vicar, who had died while Darwin was abroad. In this volume, Malthus argued that organisms, if left perfect freedom to breed and unlimited room in which to multiply, would fill any conceivable area in a very short time. The only limits to their increase were space and food. So far as man was concerned, propagation was controlled by reason, although in his case also the same limitations were existent and active, and these he proceeded to enumerate and illustrate from the histories of different nations.

Darwin wrote out his theory in 1844, but, instead of publishing it at once, he spent the next fifteen years gathering data bearing on the various aspects of the subject, conducting experiments and, so to speak, polishing the rough marble into the perfect statue. During this period also he was busily engaged in working out other problems suggested by, or connected with, his main thesis, the gist of which latter was known only to a few very intimate friends. At length, in 1856, at Lyell's request, Darwin began to expand the preliminary sketch of his theory, which he had written in 1844, so as to bring it into book

form, but with no immediate intention of publishing. In May, 1857, he wrote: "I find the subject so very large, that though I have written many chapters, I do not suppose I shall go to press for two years."

But earlier publication was forced upon him by the appearance of a new worker on the same problem. This was Alfred Russel Wallace, a young architect, who had some years previously exchanged his practice for a life of travel and exploration in Brazil and Malaya, and with whom Darwin had had some correspondence on natural history subjects. Wallace tranmsitted to Darwin an essay entitled "The Tendency of Varieties to depart indefinitely from the Original Type," the outcome of his observations and meditations amid the tropical forests of the Eastern Archipelago, and which, as Darwin says, was in effect an admirable abstract of his own unpublished work. After consulting his two most intimate friends, Lyell and Hooker, he decided to publish Wallace's essay and an abstract of his own book simultaneously, and the two papers were read to the Linnean Society on July 1, 1858—a truly historic date, and one to be remembered by every student of science. A little over a year later appeared the famous volume "On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life."

The Origin of Species.—Perhaps the easiest way to obtain a grasp of the theory expounded in this remarkable work—"one of the hardest books to master," as his disciple Huxley called it—is to follow the outline given by Wallace in an article on "Creation by Law," which appeared in 1868 in the *Quarterly Journal of Science*. Wallace's demonstration is in the form of a table consisting of two parallel columns, the first containing proved facts, the second, legitimate deductions from these facts, which deductions are afterwards transferred to the first column and used as proved facts in turn. The table is a very brief one, but each sentence really represents a volume. It may be well to give the table just as Wallace published it, and add a few sentences by way of explanation.

A Demonstration of the Origin of Species by Natural Selection.

Proved Facts.	Necessary Consequences.
1. Rapid increase of organisms. 2. Total number of individuals stationary.	3. Struggle for existence, the deaths equalling the births on the average.
3. Struggle for existence. 4. Heredity with variation, or general likeness with individual differences of parents and offspring.	5. Survival of the fittest, or natural selection—*i.e.*, on the whole, those die who are least fitted to maintain their existence.
5. Survival of the fittest. 6. Change of external conditions, universal and unceasing.	7. Changes of organic forms to keep them in harmony with the changed conditions; and as the changes of conditions are permanent changes, in the sense of not reverting back to identical previous conditions, the changes of organic forms must be in this sense permanent and thus originate species.

Beginning with "proved facts," we have first the undoubted fact that organisms, if left to themselves and given abundant food and space in which to multiply, increase at an enormously rapid rate. Huxley on one occasion made a calculation that if a plant required 1 square foot of ground on which to live, and if it were given a "fair field and no favour," and if it produced only fifty seeds a year, which could be effectively scattered over the surrounding ground, then in ten years, assuming all the plants survived, there would be 1,953,125,000,000,000 plants in existence of this particular kind, and since the whole land area of the globe amounts to about 1,421,798,400,000,000 square feet, there would not be nearly sufficient space to hold them !

The second fact is that the total number of individuals of any species remains, on the whole, fairly constant. If there be, say, 1,000 dandelion plants on a neglected lawn in any one year, and if each plant produces 100 seeds, we do not expect to find 100,000 dandelions in the year following; there may be 1,100 or only 900, but the number remains approximately the same. The obvious conclusion is that there is a constant struggle for existence going on, quite unconscious, of course, in which the deaths on an average equal the births.

Accepting this struggle for existence as a proved fact and transferring it to the first column, we note the admitted facts

that offspring, although resembling their parents in all essential particulars, show individual differences of their own; in short, we are forced to accept the facts of heredity and variation. The conclusion to be drawn is that, on the whole, those of the offspring that show any variation which gives them an advantage, however slight, over their neighbours are more likely to survive. This we term survival of the fittest, or natural selection.

Finally, accepting survival of the fittest as a proved fact, and coupling with it the known fact of the universal and unceasing changes in external conditions, we draw the conclusion that there must be corresponding changes in organic forms to keep them in harmony with these changing conditions. But these changes in external conditions never revert to identical previous conditions, and so the changes in organic forms must also remain permanent—until the environment alters.

"It is doubtful," writes Huxley, "if any single book, except the 'Principia,' ever worked so great and so rapid an evolution in science, or made so deep an impression on the general mind. It aroused a tempest of opposition and met with equally vehement support, and it must be added that no book has been so widely and persistently misunderstood by both friends and foes."

During his voyage in the *Beagle* Darwin suffered much from the effects of a serious illness contracted at Valparaiso, and this left its mark upon him to such an extent that, as he tells us in his autobiography, he never really recovered his initial health and strength. "My chief enjoyment and sole employment throughout life has been scientific work, and the excitement from such work makes me, for the time, forget, or drives quite away, my daily discomfort. I have, therefore, nothing to record during the rest of my life except the publication of my several books." After 1842 Darwin removed from London to a country residence at Down in Kent, where he spent the remainder of his years. That historic residence has lately been purchased as a national property to be held in remembrance for ever of its illustrious occupant.

Darwin's other Biological Works.—In addition to the "Origin," Darwin contributed many books and other publica-

tions on almost every branch of natural history, any one of which would have earned him distinction had they not been overshadowed by the great classic that has made his name immortal. He wrote: "On the Various Contrivances by which Orchids are Fertilised by Insects," "On the Effects of Cross and Self-Fertilisation in the Vegetable Kingdom," "On Different Forms of Flowers on Plants of the Same Species," "On Insectivorous Plants," "On Climbing Plants," and "On the Power of Movement in Plants." In 1863 he published "The Variation of Animals and Plants under Domestication," really an expansion of the first chapter of the "Origin," and later, a volume on "The Descent of Man," a book which created almost as great a sensation as the "Origin" itself.

In the beginning of 1882 Darwin's health, always feeble, began to give way very rapidly, and he breathed his last on April 19 of that year, at the age of seventy-three.

It had been the wish of his family that he should be buried at Down, but they bowed to the widespread feeling that a man so illustrious should find his resting-place in the national Valhalla; so on April 26 his funeral took place in Westminster Abbey, attended by representatives of all the great nations, as well as by very many distinguished personages and personal friends. Appropriately enough he lies only a few feet away from his only compeer, Sir Isaac Newton, and his tomb bears the inscription he would have regarded as most fitting in its simplicity:—

CHARLES ROBERT DARWIN
BORN 12TH FEBRUARY, 1809
DIED 19TH APRIL, 1882.

"The lapse of time—with the truer proportions that distant vision gives—will show the figure of Charles Darwin towering alone above all others in the history of philosophy" (Graham Kerr).

SCIENCE OF TODAY

In the preceding pages we have followed the story of scientific discovery from the earliest times down, approximately, to the middle of the nineteenth century. We have seen the bud opening in the spring when the giant form of Sir Isaac Newton "turned darkness into light," and we have traced the evolution of the young shoot into the leafy branch, but we recognised also that in the axil of each leaf there lay another bud destined to unfold in its turn.

Some of the most striking of the developments we have witnessed during our own lifetimes have been in the region of inventions—*i.e.*, the applications of scientific knowledge to matters of everyday life. Even to enumerate these would occupy far too much space, so that we must confine ourselves to sketching very briefly some of the chief discoveries in pure science, leaving the detailed story of their applications to those specially competent to deal with such matters.

The Interrelationships of the Sciences.—At the very outset we have to recognise that it is impossible to separate the advances in one science from those in another. Astronomy, for instance, has taken advantage of discoveries in physics to measure the distances of the stars and to analyse their composition; physics and chemistry have become so inextricably blended that we now have professorships of physical chemistry in our universities; geologists have called in radioactivity to aid them in determining the age of the earth; chemistry and biology have joined hands in bio-chemistry; in short, the boundaries of the different sciences are fast breaking down, and the most interesting of the problems yet unsolved lie in these borderlands where two or more sciences meet.

The Multiplicity of Workers.—Where a century ago comparatively few workers were tilling the fields of science, there are now thousands, the great majority, perhaps, adding very minute fragments to the rapidly growing mass of data; but a

few greater minds are arranging these data into co-ordinate wholes and deducing general principles from their study. Anyone who has undertaken research in a scientific subject is only too conscious of the difficulty of collecting and digesting the publications bearing on the problem on which he is engaged, and that fact is brought home to him in a striking manner by the contemplation of the volumes published in any one year which merely enumerate the titles of works dealing with any one of the sciences.

The Unity of Science.—At a recent meeting of the British Association for the advancement of Science (1926), the distinguished head of the astronomical department of Cambridge University, Professor A. S. Eddington, made a very interesting and striking comparison between three things which at first sight do not appear to have much in common—viz., a star, an atom and a man. A star like our sun, he told his audience, belonged to a system embracing some 300,000 million stars, most of them with diameters measurable in hundreds of thousands or even millions of miles. These stars, he said, were scattered through space at inconceivable distances apart, and, further, that our whole stellar system was one of many, for nebulæ may be " island universes " far outside the galaxy to which our system belongs. A drop of water, he told us, contained " several thousand million million million atoms," each of which was probably one hundred-millionth of an inch in diameter, and yet within the atom are electrons whirling round a central nucleus, like planets round a sun, and just as far from it comparatively as the planets are from our own sun. On the one hand we had the infinitely great, and on the other the infinitely small. About midway between these two extremes came man. His body consisted of atoms so numerous that the number could be expressed only by ten followed by twenty-seven noughts, while ten followed by twenty-eight noughts might represent the number of human bodies required to form a star. So " from his central position man can survey the grandest works of Nature with the astronomer, or the minutest works with the physicist. The road to a knowledge of the stars leads through the atom; and important know-

ledge of the atom has been reached through the stars" (*Stars and Atoms*).

What discoveries the years to come may hold in store for us we know not, but we may feel assured that, just as a stone dropped from a height falls more and more rapidly from its point of departure until it reaches the earth, so science may advance with ever-increasing strides from year to year.

Modern Physics and Chemistry

As the subjects dealt with are to be rendered intelligible to those who have had no previous mathematical training, it will be necessary to simplify the treatment of each as much as possible, so that the reader may not feel discouraged by being suddenly confronted with formulæ, simple enough, perhaps, to the expert, but conveying little or no meaning to the average individual. But in reading what follows it will be found convenient and helpful to consult from time to time the table of useful data given at the end of this book (p. 466).

It is no exaggeration to say that if a student, reasonably conversant with the problems of physics and chemistry as they were taught fifty or sixty years ago, had fallen asleep then, and, like Rip van Winkle, had awakened in the year 1930, he would have found himself in another world, and it would have taken him much time, labour and thought to adjust himself to the new outlook. It is only by wholesale omission of many important developments that we can hope to crowd into a few pages more than a fragment of the new knowledge of Nature and her works, that has been wrested from her by the efforts of the brilliant scientists of the present generation. All that we dare aim at, is to outline the trend of modern enquiries into what the Roman poet, Lucretius, called the "nature of things." To attempt to do more would be to defeat the very aim of this book, and to lose sight of the wood in the contemplation of the individual trees.

Heat and the Kinetic Theory.

We have seen (pp. 117-122) how slow was the emancipation of the scientific mind from the old doctrine that heat was a substance ("caloric"), and how gradually it became recognised that heat was merely a special mode of motion, and was eventually (pp. 130, 131) identified as one of the forms of energy. Kinetic energy is the name of this energy due to motion, being, for all ordinary velocities, in fact proportional to the mass of the moving object and to the square of its velocity. This simple law can be put $E=\frac{1}{2}mv^2$, where E is the kinetic energy, m the mass, and v the velocity, and this law is true of all material objects moving at any speed, except such as approaches the velocity of light (see p. 295).

For instance, a motor-car weighing 2 tons travelling at a speed of 20 miles an hour has twice the kinetic energy of one of 1 ton at this speed. It will do twice the damage in a collision and require twice the braking-power to stop it within a given distance. But if one of two cars of the same weight is travelling at twice the speed of the other, say 40 miles an hour as against 20 for the other, the faster car will possess 2^2, that is 4 times the kinetic energy, and if this energy unfortunately took the form of smashing things up in a collision, there would be 4 times the damage.

Exactly the same thing, on a vastly smaller scale, applies to the minute particles or units of matter which we call molecules, and so long as they are sufficiently free as to be able to move finite distances, as in a gas, it can be shown that these infinitesimally small particles follow the above law. The motion of these particles is equivalent to heat—the higher the temperature the greater the velocity; and moreover, heat is a mode of motion (more restricted in the case of solids and liquids) for every form of matter. It is a very simple conception, and yet among the great triumphs of the nineteenth century must be numbered this recognition, that it is the vibratory and rotatory motion of ordinary molecules that endows matter with the heat which we define by temperature, and gases with their expansive tenden-

cies. This is the kinetic theory, the mathematical elucidation of which is principally due to Clausius and Clerk-Maxwell (p. 476). Long before the actual sizes or shapes of molecules were known, the calculations were made on the simple assumption that they consisted or behaved as small elastic spheres, which, by their motions and collisions, increasing as the temperature increased, produced not only the effect of temperature but also the effect of pressure, by the continual bombardment of the walls of any vessel containing them. These conclusions have been abundantly verified by the later researches of the twentieth century, and we know now a great deal about the sizes and shapes of molecules, their prodigious numbers under ordinary conditions even in the smallest bubble of gas, their "free path" which is the average distance of run before colliding with another molecule, the enormous number of collisions per second, and so on.

It would be beyond the scope of this book to give the mathematical or experimental proofs derived from the mass of data which has been accumulated; and in any case the magnitudes involved are so enormously great or small, as the case may be, that they convey meaning only to the mathematician or physicist. For example, the number of molecules at 0° C. and normal barometric pressure (760 mm.) in 1 c.c. (p. 466) is the same for all gases (Avogadro's law) and amounts to $2{\cdot}7 \times 10^{19}$, which means 2·7 multiplied by 1 followed by 19 noughts. The mean velocity is different for different molecules (greater for light ones like hydrogen, being, as the formula on p. 224 indicates, inversely proportional to the square root of weight, m, of the molecule divided by 2); it is about a mile a second for hydrogen at ordinary temperature and about 500 yards a second for the component molecules of air. With the crowded numbers and these high speeds, it will be readily imagined that the molecules cannot get very far without a collision, and since for different molecules, at a given temperature and pressure, the numbers are the same while the speeds are not, the free path will depend on the gas. For hydrogen molecules it is less than $\frac{2}{100000}$ centimetre; but if the pressure is reduced (and so the number of molecules) the free path will be correspondingly greater. At the lowest attainable vacua of the laboratory there are still millions of molecules per

cubic centimetre, and the free path is about 100 yards. The tenuity of nebulæ (see p. 271) is so slight that molecules have an enormous range, which may amount to millions of miles before they collide with another—this in the outer rarefied regions.

A sudden reduction of pressure on any gas causes a fall of temperature because of this increase of free path—there is less agitation in a given volume; and conversely compression, which reduces the free path and causes greater agitation in a given volume, heats the gas. This temperature fall or rise due to change of pressure is known as the adiabatic change, and it has great importance in connection with the physics of the atmosphere. This is dealt with on p. 366, and it is sufficient here to point out that the change is strictly reversible and of the utmost value for taking away heat from a gas, when it is desired to reduce the temperature greatly, say for purposes of liquefaction by strong cooling. Thus if a gas is compressed in a perfectly insulated vessel there is a rise of temperature (which can be calculated with great accuracy from the adiabatic laws), and if now the pressure is reduced to what it was initially the temperature falls back to what it was initially; but if the compression-heat is withdrawn (by cooling) before decompressing the temperature will be lower than what it was initially, after the pressure is removed. And by repeating the process all gases can be so cooled as to liquefy them.

Adiabatic Laws.—The adiabatic laws are really derived from the law of Boyle (p. 50), which states that the pressure is inversely proportional to the volume, if the temperature is adjusted so as to remain constant, and from the law of Charles and Gay Lussac, which states that the volume is proportional to the temperature in absolute (not Centigrade) degrees, if the pressure is adjusted so as to remain constant. For example, if a litre of any gas at 0° C. and 760 mm. pressure (30 inches of mercury) is heated to 273° C., the pressure being kept constant by allowing the gas to expand, the volume will then be 2 litres, because the absolute temperature has been doubled (since the initial temperature 0° C.=273° absolute).

We can now better understand the absolute scale of tempera-

ture, since it is from the zero absolute ($-273°$ C.) that temperature-functions in all laws of physics start—it is indeed the zero at which all heat vanishes—*i.e.*, all molecular motion. We cannot reach absolute zero in the laboratory, though points have been touched only a little above by adiabatic cooling, involving the successive liquefaction of air, hydrogen, and last of all helium, which has the lowest boiling-point of any known substance.

Theoretically by Charles and Gay Lussac's law a gas on cooling to this zero temperature should vanish to zero-volume, which is of course absurd. In practice this does not happen, for the reason that the law ceases to hold before zero is reached by a change in state of the gas, to the liquid (or solid) condition. In its simplest form the combined Boyle-Charles-Gay Lussac law may be stated in the form, that the product of the pressure multiplied by the volume is equal to the absolute temperature multiplied by a constant (R), and it is commonly written:—

$$pv = \mathrm{RT}.$$

But this simple equation takes no note of factors which are ordinarily present—namely, the actual size of the molecules themselves (small in comparison to the bulk of the gas it is true, but yet not infinitely small) and a certain attraction (a sort of adhesive attraction) which these molecules have for one another, which is very noticeable when their concentration becomes great, near the point when the gas is going to liquefy. When these corrections, which were first elucidated by van der Waals, are incorporated in the above law a complete equation can be deduced, and from this foundation the adiabatic laws can be built up. The mathematical expression of these laws, together with the second law of thermodynamics (p. 131) has led to an elaborate treatment of the pressure-temperature changes in the atmosphere, involving a special conception of *entropy*, which it is beyond the scope of this book to deal with; and in the hands of the astro-physicist they have enabled the constitution of the stars to be elucidated with great nicety.

Liquids.—Although the greatest triumphs of the kinetic theory are related to researches on gases, it must be remembered that this theory has greatly facilitated the elucidation of the

nature of liquids and solids. The distinction between the three fundamental states of matter—viz., gas, liquid, and solid—is essentially a distinction in the concentration of the molecules and their degrees of freedom, due to the physical conditions (temperature and pressure) imposed.

A state of matter, in scientific language, is known as a *phase,* and certain well-defined principles have been elucidated by the American physicist Willard Gibbs, governing the conditions of coexistence of separate phases and their mutual transition into one another. All that is necessary here is to try and explain what is the difference between a solid, liquid and gas. In terms of the kinetic theory it is easy to see that there is something approaching perfect freedom in the case of gas molecules. A "perfect" gas is not known, though hydrogen approaches this condition, it being understood by the word perfect that the above laws of Boyle, Charles and Gay Lussac hold for all conditions of temperature and pressure; that in fact the individual molecules should behave as perfectly elastic spheres of zero-volume and having no physical attraction for each other. In so far as these two conditions are never quite realised, a gas shows smaller or greater deviation from the gas laws and behaves as a jostling crowd of molecules, showing some though small interest in each other, like a swarm of bees. Their movements, however, are free, irregular, and vigorous; the molecules are independent and perform their own zig-zag course as they collide with others, but they are not otherwise restricted.

A liquid, on the other hand, is in very different case. Here the molecules find themselves in virtual contact owing to the conditions prevailing; they are not free, simply because they cannot escape each other's influence, though they have sufficient freedom to work their way slowly between other molecules into new positions, this motion being more active the higher the temperature. It is like a closely packed crowd of human beings, where each individual is trying to worm his way to some other position, whereas a gas is more like a thinly dispersed gathering of people, running to and fro, on some open heath, with plenty of room up to a point, but not sufficient to prevent constant collisions. Perhaps a better analogy for the liquid condition is

a canister full of fine polished leaden shot, kept in a continual state of agitation by some imaginary stirring agency within. Such particles continually flow over each other, they can be poured out of the vessel *en masse*, but they will not cohere.

Solids.—A solid is still more restricted so far as molecular freedom is concerned. The units of the crowd here are literally tied together, just as if a mob of human beings joined hands in such a way as to restrict all independent movement. The people can "jiggle" about, bob up and down and even twist round to some extent, but they cannot get away from each other till they loose hands. This is only a rough analogy to the solid or crystalline state, but it has been disclosed as applicable to molecules by the penetrating researches of Sir William Bragg and his followers, using the method of X-ray analysis. This X-ray photographic method actually reveals the positions of the atoms and molecules in solids, their distance apart (of the order of a few Ångström units—see p. 259), the angle of the imaginary lines joining them, and so on. It is a wonderful story, and the surprising feature of the crystal lattice of compounds, so revealed, is that the molecules, as such, seem to be less apparent as units than are the atoms comprising the molecules. Did we not know from other sources that the molecules are the fundamental units, we should almost imagine from X-ray analytical methods that the units were the atoms. It is, of course, the effect of molecule-packing in definite-shaped contiguous cells which repeat themselves, but in which the atoms show up in the photographs, that gives this rather erroneous impression. And, of course, it must not be imagined that these atoms are seen—they are, of course, much too small. What is seen is their effect on X-rays in producing figures by which their positions and distances can be identified and measured.

A crystalline solid, then, is a molecular structure, in which the atoms are spaced in a practically fixed position, so as to form some geometrically shaped group or cell, specific for each substance, a cell which is endlessly repeated throughout the mass of the crystal. The number of such cells in a gram (p. 466) of solid is of course vast, but known in many cases. The number may be gathered from the case of water, one gram of which

contains $3{\cdot}3 \times 10^{22}$ molecules ($3{\cdot}3 \times 1$ followed by 22 noughts), and when water crystallises to form ice these molecules group themselves into cells of a few molecules, each packed into a rather loose type of hexagonal lattice. In the latter, each oxygen atom is at the centre of gravity of four neighbouring equidistant oxygen atoms, from which it is separated by a hydrogen atom, so that two of the latter are found in conjunction with each oxygen atom.

The same kind of thing is found in all crystalline solids, and if it is asked what are the forces binding the molecules together in these geometrically shaped cells, the answer is to be found by appealing to the same kind of attractive force which was referred to (p. 227) in the case of molecules of gases, and which tends to make them "imperfect." It is a force quite different from, though doubtless related to, that which binds the atoms themselves together in forming the molecules. This force binding atoms, known as chemical affinity, is electrical, and, though not yet completely understood, it is in some way connected with the movements of electrons which surround the nuclei of atoms, and of which we shall have a good deal to say later on (p. 246). The force binding molecules together is probably also electronic, being in the nature of so-called residual affinity, and it is probably of the same kind as that which we call ordinary adhesion.

These forces, tending to bind molecules together, are in opposition to heat, which by endowing the molecules with greater kinetic energy tends to loosen them. In liquids both opposing forces are in equilibrium, and so the molecules of liquids have a considerable degree of freedom. But the moment the kinetic energy falls to a certain value—*i.e.*, at a perfectly definite temperature (the freezing-point) for each substance—it ceases to effectively oppose the forces of residual affinity of the molecules, and the liquid solidifies. The molecules of solids still have, however, some degree of freedom within their apparently rigid crystalline lattice, so long as the temperature is above absolute zero, and it is this restricted vibratory movement (in the three dimensions of space) which confers upon them the property of being warm.

Viscosity.—There are certain types of liquid which do not crystallise readily, if at all, when cooled, but instead become thicker and more treacly, and eventually may appear to be solid, though not truly so in the crystalline sense. We all think of glass as a solid, or even toffee, but they are rather to be regarded as liquids of very high viscosity, since they possess none of the properties of crystalline solids. Such substances are said to be *amorphous*. The case is better illustrated by considering liquid viscosity more closely, a property due to those forces referred to already, tending to bind the molecules together and dependent largely on the chemical nature of the liquid substance, but greatly affected by temperature. For example, the chemical compound known as common ether (used in anæsthesia and also as a solvent) has a very low viscosity at ordinary temperatures—much lower than that of water, for instance. It is much more mobile than water and will run through a narrow orifice or tube much more rapidly. Also, water when hot may be six times more mobile than when cold, as shown by the more rapid rate at which it will pass through a narrow orifice—its viscosity is reduced by rise of temperature, as is the case with all liquids (provided something else does not happen to interfere with this change). Common pitch is quite a mobile liquid at about 180° C., but as the temperature falls the liquid becomes thicker and thicker, till when cold its viscosity is so great that pitch behaves very like a solid in its resistance to deformation. Glass is similar, and even water and many other liquids will behave similarly and assume a glassy condition (amorphous) if cooled well below their freezing-points, provided that certain conditions are observed, difficult to attain, to prevent crystallisation, which is the normal behaviour of such liquids. It is really a matter of time, because, if the temperature can be got many degrees below the freezing-point quickly enough, the molecules at this low temperature are now so sluggish in their movement that it takes a very long time for them to arrange themselves in the orderly geometrical pattern of crystals; indeed, the colder the glassy form is the more stable it will be.

The preceding description of the three fundamental states of matter is of course a very simplified one, and omits all chemical

considerations including influence of admixture. In practice the whole problem is, of course, highly complex, but, nevertheless, the simple picture portrayed is tolerably faithful for purposes of illustration. It means that, apart from accidental complications, any piece of matter can be imagined (and frequently induced) to exist in all three states or phases—solid, liquid, and gas or vapour. [The term vapour is a loose one, generally, however, connoting the gaseous condition near the point of condensation to liquid.] That is to say, the state or phase of a substance is determined by the conditions (temperature and pressure) imposed. A substance may appear as a solid, as a liquid, or as a gas, subject, however, to the restriction that it is sufficiently stable, chemically, over the temperature range involved —*i.e.*, to remain undecomposed. Thus cellulose (in wood) is a solid, and it cannot be liquefied or converted into gas, in the same kind of way that ice can be converted into water and steam, for the reason that its molecules are relatively unstable chemically, and if you heat them too much in the attempt, say, to gasify them, you simply break up these molecules into a heterogeneous crowd of other molecules by chemical decomposition. Apart then from this, as it were, accidental factor, matter normally is capable of existing in three states, according to the temperature and pressure. Low temperature or high pressure tends to induce the solid or liquid condition; the converse tends to induce the gaseous condition. But, as might be expected, the chief factor determining the state of matter, under conditions obtaining on earth, is the nature of the matter, that is to say the kind of molecules, their size and mass, and the chemical or physical attraction they have for each other. And so it comes about that there is an endless diversity in the kind of molecules with which we are familar as ordinary matter, say, on earth, and a corresponding endless variety of physical (and chemical) properties.

Broadly speaking the simpler and less massive molecules, like those of, say, oxygen or water, will have a tendency towards the gaseous state, and require more or less high pressures and low temperatures if they are to present themselves as liquids or solids. On the other hand, the more complex molecules, like those of

sand (silica), iron, carbon, etc., require high temperatures in order to appear as gases. At the temperature (about 6,000° C.) of the sun's surface everything is gasified, and chemical compounds would be decomposed or dissociated into their elements, and so the molecules there practically all consist of elementary atoms.

To illustrate better the changes of state with varying temperature and pressure let us take a very simple example, water. Imagine a little water contained in an hermetically closed glass tube containing nothing else (*i.e.*, all air originally in the tube having been extracted). There is an empty space above the water in the tube, which is not strictly empty but filled with mobile molecules of water as invisible gas or vapour (steam). And if we measure the pressure of this gas in the tube, as we could do by fixing a manometer (p. 69), we should find that the pressure increases as the temperature is increased, and that there is indeed for every temperature an exactly corresponding pressure. This is known as the *vapour pressure* of the liquid (whatever it is, for the principle applies to all cases). Moreover, as we raise the temperature we find that some of the liquid disappears, and a corresponding increase occurs in the concentration of the steam molecules in the space above. [Concentration is a term of great significance in science: it denotes the weight or total mass in unit volume.] When we reach a temperature of 100° C. in our closed tube the pressure is found to be exactly 760 mm., which is that of the atmosphere (average) at sea level —*i.e.*, one atmosphere or normal barometric pressure. If we go on heating above 100° and the tube is strong enough to withstand the increasing pressure, nothing apparently happens to the liquid water (it does not boil) except that it diminishes in quantity whilst the steam concentration increases. In fact, the pressure increase now becomes very much more rapid than that of the temperature increase. It was so all along and the two are not proportional, but at high temperatures the pressure effect becomes steeper and steeper. And a very strange thing happens when 365° C. is reached. At this point the surface of the liquid water becomes hazy and not sharply defined as it was before; and if any attempt is made to raise the temperature beyond this, the liquid simply disappears and the whole tube is filled

with one state of matter. It is all now in what we call the gas or vapour phase. Other liquids show similar behaviour, each at its own particular temperature, and this temperature above which the substance can never appear in the liquid phase is known as the *critical temperature.* The pressure corresponding is called the critical pressure, and for water it is nearly 195 atmospheres, but however big the pressure no substance can appear in liquid form above its critical pressure. Incidentally this is the reason why all the earlier attempts to liquefy air, hydrogen and other so-called "permanent" gases failed, because it was not then recognised that the temperature must be lowered below their respective critical points before liquefaction could appear.

Returning to our tube of water let us now cool it down. Exactly the reverse changes occur to those outlined above, till we come back to ordinary temperatures, by which time the pressure inside the tube is only about 15 mm. or, say, only 2 per cent. of one atmosphere. If we go on cooling below this, the vapour pressure steadily falls till at 0° C. the water begins to go solid by crystallisation and eventually only the ice phase is present. The pressure of the gas or vapour in the tube when ice and water are present is only 4·6 mm., and it remains at this till no liquid is left, showing that ice has an appreciable vapour pressure. If we go on cooling our tube to still lower temperatures the ice of course remains, but its vapour pressure steadily diminishes; nevertheless it is appreciable at quite low temperatures, and even at $-50°$ C. it is ·03 mm.

If we carry out a similar set of observations with water in an open glass vessel, such as a beaker, there is this important difference to bear in mind, that the pressure above the water is no longer its own vapour pressure—*i.e.*, a function of the temperature—but constant. It is, in fact, about 760 mm., or the pressure of one atmosphere. If we cool the water down to freezing-point ice will begin to form at a very slightly lower temperature than it did in the tube, because of course the pressure is greater and the melting-point of ice is lowered by increasing the pressure. The effect is relatively small, but nevertheless the true constant temperature in the equilibrium, ice-water-steam, where all three phases coexist,

is not quite the same as the temperature of an ice-water system under the higher pressure of one atmosphere, but a trifle higher. The true point, called the triple-point, is an absolute constant of nature, and its recognition by Willard Gibbs and later workers has led to a wonderful superstructure of theory known as the Phase Rule, by which the degrees of freedom of the varying phases of different forms of matter have been elucidated. The Phase Rule is much too complex to enter into here; suffice it to say that this physico-mathematical instrument has been of signal service, not only in the development of chemistry and geology in defining the limits of existence of crystals and rocks, but also in the successful exploitation of chemical discovery for large-scale industrial manufacture. Returning once more to water, let us heat our beaker containing it and enquire why it behaves differently from the water in the closed tube. For as everyone knows it evaporates constantly and when a certain temperature is reached the water boils. After what has been said it should be easy to understand why. On the kinetic theory the molecular velocity or agitation increases as the temperature rises, the velocity average of the molecules in the liquid phase being constant for any temperature. At the surface of the liquid some of these molecules escape by bursting through the topmost layer and so appear above as gas molecules, and, conversely, the velocity of the molecules in the vapour space above will carry some of them back through the surface skin of liquid. In this battering of molecules to and fro there is thus a continual interchange going on between molecules on both sides of the surface; and in a closed tube when equilibrium is established for any particular temperature there will be, on statistical average, as many escaping from the liquid to the gas-phase as vice versa. This equilibrium, however, changes when the temperature is raised and in such a manner that at the higher temperature a much greater number (concentration) are required in the gas-phase in order to compensate the greater number fired into this phase from below. This expression "fired from below" is crude, but it sufficiently meets the case, for the problem is really one of bombardment, and the point to remember is that for every temperature in an enclosed space there is an equilibrium in which an equal number

of projectiles pass each way. This is equivalent to saying that the vapour pressure is always constant for any fixed temperature, and that it rises as the temperature rises because the speed and number of the projectiles are increased.

Evaporation.—We now see why the case is different in an open vessel. Evaporation is, of course, due simply to the steady loss of these projectiles, since in the open most of them get away into the air; only relatively few can return, not many as in the case of a closed tube. Evaporation will be more rapid at a higher temperature, for obvious reasons, than at a lower one, and most rapid for any temperature when a draught of air above the surface carries away the gaseous molecules of steam and so reduces the number at any instant which can return. For this reason although evaporation of water, which takes place slowly at 0° C. or even (more slowly) with ice and snow at much lower temperatures, can be fairly rapid in the open on a cold, windy day; and the rate of evaporation will be higher the higher the wind and the drier the air, just as it will be lowest on a cold, damp, still day.

Ebullition.—Returning to our open beaker of water which we are heating, let us continue till the boiling-point is reached (100° C.). At the boiling-point the vapour pressure of the liquid just amounts to one atmosphere, and beyond this the pressure (in an open vessel) cannot go. So if more energy in the form of heat is supplied something has got to happen to the agitated molecules of the liquid; and if the latter, as is usual, is heated from below, gas bubbles of steam collect and escape. The liquid is said to boil, and the boiling-point of *any* liquid is the temperature at which its vapour pressure just equals the super-incumbent pressure.

But it must be emphasised that the liquid will not boil if maintained merely at its boiling-point. There is, in fact, very much more kinetic energy in a given mass of steam molecules than in the same amount of water at the same temperature. Before the water molecules can be endowed with this large extra amount of energy, it is necessary to supply it (latent heat of vaporisation—see p. 125), as, for instance, is done usually by means of a fire or gas flame underneath, the energy of which is

derived chemically by the combustion of carbon compounds. So water will boil quickly or slowly, say, in a kettle, according to the amount of energy supplied, this energy being transformed into the new form of kinetic energy of the steam molecules.

Suppose the pressure above instead of being atmospheric is raised, say, tenfold, as it is in a closed steam boiler. The boiling-point is now much higher (180° C.), and of course the concentration of the steam as well as its kinetic energy greatly increased; and so also its power of doing useful work in an engine. On the other hand, suppose the pressure is reduced below one atmosphere, as it is on mountain-tops; the boiling-point is now below 100° C., and cooking watery food would accordingly be more difficult at high altitudes, because at the lower temperature the speed of the physical and chemical changes involved in cookery is lowered as the speed of the molecules (kinetic energy) is reduced. For example, it would be impossible to cook at all by boiling in open vessels on the planet Mars, because the atmospheric pressure (and therefore boiling-point) is too low.

Distillation.—In fact, the boiling-point of any liquid at any pressure is known if the vapour pressure figures are known, because the two are identical. So for example we know that a water boils at 80° C. at about half an atmosphere, at 60° C. for a quarter atmosphere, at 40° C. for one-tenth atmosphere, and at ordinary temperature at ordinary laboratory vacua (one-fiftieth atmosphere). This principle of reduced boiling-point for reduced pressure is enormously used in industry, in what is called vacuum distillation. Ordinary distillation, which may be conducted on the small scale in a glass retort, or in a flask provided with suitable side-tube, consists in heating the liquid continually to make it boil, the vapour passing away continually through a cooled tube or coil, called a condenser, the function of which is to liquefy the vapour. The object of such distillation is to purify the liquid and separate it from accompanying substances, which are either not volatile at the boiling-point of the liquid distilled (say, salt dissolved in water) or have a higher boiling-point and tend to come over later in the distillation (this being called fractional distillation). But there are many substances which are rather unstable and tend to decompose on heating

to their boiling-point at atmospheric pressure (glycerine, for example, which boils at 290° C.). In such cases the practice is to resort to vacuum distillation, better described as distillation under reduced pressure (because a complete vacuum is never attainable), and so by working at much lower temperatures obtain all the separation-advantages without accompanying destruction.

The Inert Gases of the Air.—We have seen how not only the ancient classical writers but also the physicists and chemists of the period after the rebirth of science concerned themselves with the nature and properties of supposed elements, the four so-called "Aristotelian Elements": fire, air, water and earth. We have also seen how, after a long period of misapprehension, fire or heat was proved by Rumford and Davy to be not an element in any sense but "a mode of motion." Water, owing to the labours of Cavendish and others, was shown to be not an element but a compound of two gases, hydrogen and oxygen, united in certain fixed proportions (pp. 143, 174).

Air was the chief "element" to receive attention, and here again a composite nature was revealed by Mayow, Black, Scheele, Priestley, Cavendish and others, who showed it to be a mixture of gases of which the chief were the elements nitrogen and oxygen. It will be remembered, however, that Cavendish, in 1784, tried to determine the exact nature of the gas left over after he had caused all the oxygen in the atmosphere to unite with hydrogen to form water, and found that about $\frac{1}{120}$ of the residual nitrogen was something that was not "mephitic air" or nitrogen (p. 175). No notice was taken till the nature of this "something" was discovered about a century afterwards by Rayleigh and Ramsay.

In 1893 Lord Rayleigh, at that time Professor of Physics at the Royal Institution, was occupied in determining the densities of various gases, and observed that "pure" nitrogen got from the air was always slightly heavier than the same gas when obtained chemically from compounds of nitrogen. He thereupon associated with himself Sir W. Ramsay, Professor of Chemistry at University College, London; and, using all the best modern methods and appliances, the two scientists at last

were successful in showing that the additional weight was due to the admixture in small amount of a new gaseous element, which they christened "argon," "the lazy one," because it could not be induced to combine with any other element.

In 1895 Ramsay made his famous discovery of helium in the mineral cleveite, the gas that had been found, many years before, by Lockyer to form a constituent of the solar chromosphere (p. 164). In 1898 Ramsay and Travers prepared large quantities of crude atmospheric argon, and, by liquefying it with intense pressure and cold, followed by repeated distillations, they obtained not only helium but three other new gases, *neon*, "the new one," *krypton*, "the hidden one," and *xenon*, "the stranger," not one of which would form a compound with any other element, and so they all were named inert gases. Taken together these five gases constitute about 1 per cent. of the atmosphere, so that Cavendish, with his somewhat primitive apparatus, was not far wrong in his estimate of the amount of the strange gas present in atmospheric nitrogen. It may be said, therefore, that we are now well acquainted with the nature and composition of the gaseous envelope of our globe (see also p. 365).

§ i. Atomic Physics.

Cathode and Anode Rays.—In 1880 Sir William Crookes made a discovery that led to new methods of investigating the constitution of matter. He was studying the effects produced by sending electric discharges through tubes from which as much as possible of the contained air had been extracted—"vacuum tubes" as they were called. It had long been known that an electric current could not be induced to pass through gases save at a very high voltage. Crookes tried whether the discharge would take place in more and more rarefied pressures, and obtained some very remarkable results.

He carried out his experiments in tubes similar to those seen in Fig. 91. When, by means of an air-pump at first attached at P, before the tube was hermetically sealed, the air pressure within was greatly reduced, the gas became luminous. At the cathode end (1, K) there appeared a dark space, called the "Crookes dark space" (C K) followed by a glow (K G),

and then another dark space, the "Faraday dark space" (F), succeeded by wave-like extensions toward the anode (A), known as the "positive column" (P C). When the gas pressure in the tube was reduced to 0·01 mm. of mercury, the positive column disappeared, and the "Crookes dark space" filled the tube, the end of which began to glow. These kathode (cathode) rays which cause all these phenomena make mica vanes within revolve like the arms of a windmill; they can be deflected by the north pole of a magnet, and therefore must carry charges of negative electricity, as may be seen by projecting them into a cup placed in connection with a galvanometer (Fig. 91, 3, G). They may be intercepted by some article, and cast a shadow of it on the wall of the tube (4). What are these particles? Crookes regarded them as a "fourth state of matter." They are now identified with "electrons"—the ultimate and indivisible but material units of negative electricity.

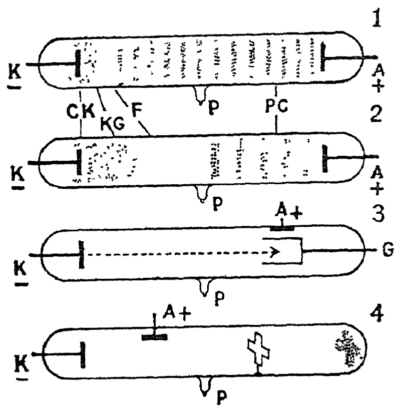


FIG. 91.—VACUUM TUBES AND CATHODE RAYS.

If the cathode be pierced with minute holes, another set of rays may be recognised travelling from the anode in the reverse direction towards the cathode pole; and these rays, under powerful magnetic influence, may be deflected also, but in a direction opposite to the cathode rays, showing them to be positive and with a mass proportional to the atomic weight of the gas in the tube. They are generally regarded as the atoms of the residual gas left in the tube that have lost one or more electrons. If an absolutely perfect vacuum could be obtained in the tube there would be no anode rays, but such a vacuum as yet is unattainable.

Röntgen or X-Rays.—In 1895 Röntgen, professor of physics at Würzburg, made a further discovery in relation to cathode

rays. He found that when they impinged on a metal plate they gave rise to a new form of radiation which, because he was unable to determine their exact nature, he called "X" or unknown rays. The important point about them was that they had immense penetrating power, a power that increased the more perfect the vacuum in the tube. Looking back to the chart of the spectrum figured on p. 107, it will be seen that X-rays range from 0·000,000,001 cm. to 0·000,001 cm. as contrasted with the wave-lengths that make impressions on the retina of the eye, which range from violet, 0·000,038 cm., to red, 0·000,078 cm. Fig. 100 shows the usual form of an X-ray tube. The cathode is a concave plate by means of which the electrons are focussed on a flat metal mirror, B, from which the X-rays emanate through the wall of the bulb. If a photographic plate, P, enclosed in a light-proof covering, be placed on a table, and an object, say the human hand, be laid on it, the rays penetrate the hand unequally. The flesh, being much less opaque than the bones, is penetrated by the rays, which are retarded or stopped by the bones. These latter, therefore, produce dark shadows on the plate. The result is a photographic negative, from which "radiographs" may be printed, enabling a surgeon to see the exact nature of a dislocation or a fracture in a bone, or the spot where a foreign body, a needle or a bullet, has lodged, as if the whole of the flesh had been dissected away. Electrons, thus discovered by Crookes and used by Röntgen to excite X-rays, by bombardment of metals, were destined to play a big part in twentieth century science, as we shall now see.

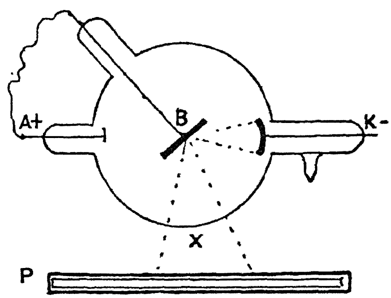


FIG. 92.—X-RAY APPARATUS.

The Constitution of Matter and the Structure of the Atom. —The reader is advised to frequently consult the table on pp. 380, 381, while reading the rather difficult pages which now follow. Before dealing with modern views, it will be as well to review the Atomic Theory as it stood at the close of the

nineteenth century, after it had surmounted the early difficulties of the first half of the century, arising from the confusion between atoms and molecules. These grave difficulties were cleared away in 1858 by the penetrating genius of Cannizaro, who showed what the true consequences were of Avogadro's hypothesis of 1811 (p. 183). This hypothesis, which enables the molecular weight to be deduced of all pure substances that can appear in gaseous form (say, by heating), is fundamental to chemistry. For if the weight of the molecule is known in terms of the weight of an atom of hydrogen as unity, the weights of the atoms composing the molecule can be deduced from the combining weights, but not otherwise. We know, for instance, that the molecule of water is H_2O, if that of hydrogen is H_2, because (1) the density of steam is nine times that of hydrogen (taken as unity) and (2) because 8 parts by weight of oxygen are present to 1 of hydrogen. For since equal volumes contain the same number of molecules (Avogadro) the water molecule must weigh nine times as much as a hydrogen molecule and therefore eighteen times as much as a hydrogen atom. So in this water molecule there must be 1 atom of oxygen weighing 16 and 2 hydrogen atoms, each weighing 1. All this rests on the belief that there are 2 hydrogen atoms in a molecule of hydrogen, which is independently proved by the fact that 2 volumes (equivalent to 2 molecules) of hydrogen combine with 1 volume (equivalent to 1 molecule) of oxygen, producing 2 volumes (equivalent to 2 molecules) of steam. A little logical thought here will show that you could not get 2 molecules of steam, of density 9, from 2 molecules of hydrogen if the latter consisted of 2 single atoms which cannot be split, but that these molecules must contain at least 2 atoms each. This will perhaps be clearer if we write the equation thus:

$$\underset{\left(\substack{\text{2 mols., therefore 2 vols.}\\ \text{density 1}}\right)}{2H_2} \quad + \quad \underset{\left(\substack{\text{1 mol.—}i.e.\text{, 1 vol.}\\ \text{density 16}}\right)}{O_2} \quad = \quad \underset{\left(\substack{\text{2 mols.—}i.e.\text{, 2 vols.}\\ \text{density 9}}\right)}{2H_2O}$$

On this line of reasoning the whole vast superstructure of chemistry has been erected, and the chemical formulæ of thousands of compounds deduced. When it is recollected that organic chemistry, with its hundreds of thousands of

compounds of known constitution, has been built up on the molecular theory founded on Dalton's atoms, without a single exception being discovered inconsistent with this theory, it is self-evident that the theory must be fundamentally sound; and that atoms, each with its own definite combining weight, have a definite objective reality and are not a mere convenient figment of the imagination. In the almost romantic development of organic chemistry during the latter half of the nineteenth century, the atoms played the part of units or bricks in molecular architecture, and the great quest was (and still is) to build these bricks into every imaginable type of structure (synthesis) or find out how they were linked together in known substances (naturally occurring organic compounds associated with life). In this great and wonderful achievement chemists did not bother their heads with the bricks themselves or what they were made of; and up to the end of the nineteenth century atoms were still regarded in much the same kind of way as Dalton had imagined them. Indivisible units they were to the chemist because, so far as could be then judged, no power could split them up into anything simpler. And even if they could, this would not affect the validity of the great truths of chemistry which had been established, and indeed which still hold. It was, of course, recognised that they might not be the ultimate stuff of the Universe, any more than a brick, which is composed of particles of clay, is an ultimate material unit. Prout's hypothesis (p. 185) had been discountenanced by the accurate atomic weight determinations of Stas (p. 252) and others, and mere speculation as to the constitution of atoms led nowhere. So that until a generation ago the generally received conception of the constitution of matter was that, on ultimate analysis, it consisted of invisible, indivisible and indestructible particles or atoms which Lord Kelvin, in 1881, estimated to be anything between a ten-millionth and a hundred-millionth of a centimetre in diameter. But as we learnt more and more of the nature of electricity, doubts began to arise as to the indivisibility of the atom. In the closing years of the nineteenth century, Sir J. J. Thomson, of the University of Cambridge, suggested that an atom consisted of two parts, one electrically positive, the

other electrically negative. The positive charge resided in a "nucleus," and the negative charge or charges in one or more "electrons" which surrounded the nucleus. This may be called the "static" theory of the atom. The electron was estimated by Thomson to be about $\frac{1}{1800}$ of the mass of a hydrogen atom, and, since hydrogen had only one electron, almost the whole of the mass of the atom lay in the nucleus.

Rutherford-Bohr Atom.—These tentative views received striking confirmation when in the early years of this century the mysteries of radioactivity (p. 273) came to be slowly unravelled. It was more particularly the behaviour of radium and uranium which forced the new views of atomic constitution on the minds of physicists, and indeed a new world of science was opening up the like of which could never have been imagined by the chemists of the nineteenth century. Bit by bit the entrancing story was unfolded, more like a tale from fairyland than the supposedly dry findings of science, but alas! complex beyond measure and completely intelligible only to the trained mind. We shall not give these findings piecemeal, as they became accepted, but attempt a very simple description of the present-day theory of the constitution of the atom.

A tremendous advance took place when in 1911 Sir E. Rutherford put forward the view, extended by Niels Bohr, that an atom might be simply a miniature solar system, consisting of a central sun—the nucleus—and one or more planets—the electrons — whirling round it. This is the basis of the planetary atom or "dynamical" theory, which is now generally accepted.

In the Rutherford-Bohr atom it is necessary to picture a state of affairs (diagrammatically indicated on p. 246, Fig. 93) in which an excessively minute central nucleus is surrounded by one or more electrons at a *relatively* enormous distance, these electrons moving round the nucleus at prodigious speeds. Practically the whole mass of the atom (*i.e.*, its atomic weight) resides in the nucleus, the revolving electrons being so light that they contribute almost nothing to the weight. To grasp the magnitudes involved it is best to consider the hydrogen atom model (1), this being the simplest of all atoms. Imagine then a central

nucleus, the so-called *proton*, surrounded by one moving electron. The proton weighs 1,840 times the electron, but its actual mass is so small that it would take about a million million million million protons to weigh 1 gram. Its size is so inconceivably minute that it would take 5,000 million million protons in a contiguous string to give the length of one centimetre. The electron while much lighter is thousands of times larger than proton. These incredibly small magnitudes have been determined experimentally and are known with a fair degree of precision, and if they convey anything to the human mind it is the vast emptiness of the atom; for when the distance of the electron from the proton is taken into account, it is found that in the normal (un-agitated) hydrogen atom this distance is about 25 million times the diameter of the nucleus (proton) and very much greater still when the hydrogen atom is endowed with increased energy, such as is associated with the high temperature of the stars. The size of the normal (undisturbed) hydrogen atom is the size of the orbit which its single electron describes round the proton, and this is such, that it would take a contiguous string of 100 million atoms to measure 1 centimetre. Some conception of the infinitesimally small magnitudes in question may be obtained by remembering that one million days ago, from today, would carry us back to 900 B.C.—that is, to a period before the rise of Greek civilisation. Whilst the actual figures representing magnitudes convey but little to the imagination, the model of the atom representing relative relationships is intelligible enough, and we may proceed to consider the simplest such model (hydrogen) further. This model is shown in rough and *not to scale* in Fig. 93, where the dark inner circle, numbered 1, crudely represents the proton-nucleus and the larger circle, with dot, the orbit of the electron. This relatively massive proton has been identified with the smallest known unit of positive electricity (marked + in the diagram), and the light electron has similarly been shown to be the smallest unit of negative electricity. Yet each are particles of matter in the sense that they possess mass and are subject to gravitation; and so in its last analysis matter (in the form of protons and electrons) is indistinguishable from electricity. This, as we

shall see presently, applies to all forms of matter—at present we are only considering hydrogen.

The electrical attraction between the proton, carrying one charge of positive electricity, and the electron, carrying one charge of negative electricity, is such that if they could come together both would disappear in a flash of radiation, the amount of which has been calculated and found to correspond in quantity to that of the cosmic rays referred to on p. 269. If, as there is reason to suppose, this can happen (in the stars and nebulæ) it involves the annihilation of matter and its replacement by an equivalent amount of energy. So far as we

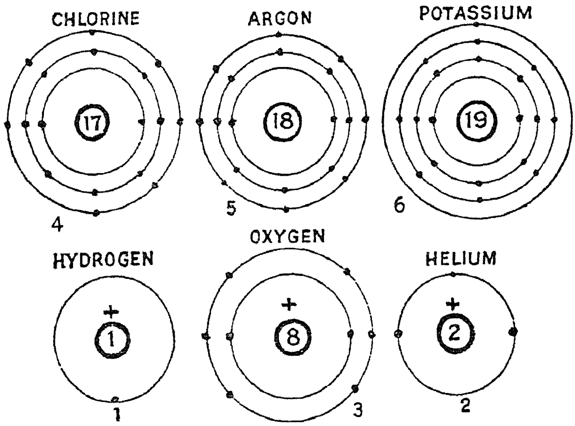


FIG. 93.—STRUCTURE OF THE ATOM.

know, however, under conditions obtaining on earth this does not happen to any appreciable extent. The electron, situated as it is at a relatively enormous distance from the proton, does not fall to it any more than the planets fall into the sun; it revolves round it instead, and this also is true of other atoms where there are heavier nuclei than a proton and two or more electrons. The latter revolve rapidly around the nucleus in definite orbits, and it is only this high speed of revolution which prevents the universal disappearance of matter in a stupendous outburst of energy. Moreover, it is this motion of electrons, at relatively vast distances from their nuclei, which confers upon the atoms of all elements their stability and specific

feature of indivisibility. So also it comes about that the size of any atom is vast compared to the size of the central nucleus, and that an atom is enormously bulky compared to the weight, nearly all of which is centred in the nucleus.

Returning to the model hydrogen atom, Bohr has worked out, by an intricate analysis, what the movements of the electron are under various conditions of stimulation, by tracing out the relation between the spectral lines of hydrogen under varying conditions of excitation. He has established clearly that the electron can have many orbits, but that these orbits are related to each other in a very simple manner. Thus they may be circles whose diameters stand in the ratio to each other 1^2, 2^2, 3^2, 4^2, 5^2, etc.—*i.e.*, 1, 4, 9, 16, 25, etc., where unity, 1, stands for the diameter, already referred to, of the orbit in the hydrogen atom in its un-excited (cold) condition. Also the orbits may be ellipses of different eccentricities, but the major axes of these elliptical orbits stand in these same ratios, 1, 4, 9, 16, etc. Intermediate orbits in no case appear. When the atom is excited to a greater activity, say by raising the temperature, the electron jumps from an inner lower orbit (say 4) to a higher one (say 9), whether circular or elliptic; and in doing so a very definite amount of radiant energy is absorbed, called a *quantum*. When an atom in an excited condition changes to one of lower energy, the electron jumps from this outer orbit to an inner one (say from 9 to 4), whether circular or elliptic, and in doing so gives out the same quantum as it absorbed in changing from 4 to 9—viz., as a definite line in the spectrum of radiation. We will explain the nature of radiation more fully later on (pp. 257-273); for the present it is sufficient to say that the emission of energy is detected spectroscopically, and that the precise orbital changes or electron-jumps can be correlated with definite spectral lines.

Let us now turn to other atoms. All matter, as we know it on earth, is made up of combinations or mixtures of the 92 elements given in the table on pp. 380, 381. These elements are numbered in a sequence from 1 to 92, for a reason which will appear presently, these being the *atomic numbers*; and of the whole sequence only two (85 and 87) are as yet undiscovered.

Each of these elements differs from the others, and there is a steadily increasing atomic weight as we pass up the series. How does this come about, and what is the constitution of these 92 kinds of atoms?

The Rutherford-Bohr model explains them very simply. Each atom is similar to hydrogen in that it possesses a positively charged massive nucleus, inconceivably small, in which practically the whole weight of the atom resides; and around this nucleus are electrons circling in definite orbits, the number of these orbital electrons being different for each element. Take, for example, the next simplest atom to that of hydrogen, helium, of atomic number 2 (see Fig. 93, 2). The nucleus has a mass rather less than that of 4 protons, but it also has 2 electrons in some way embedded in it. As it is believed that there are actually 4 protons (*i.e.*, 4 positive charges) present, 2 of which are neutralised by these embedded electrons, the *net* charge on the nucleus is $4-2$—*i.e.*, 2 positive charges. The latter therefore require 2 negative charges (as orbital electrons) to make the neutral atom of helium. Although in the diagram these 2 electrons are represented as lying in the same ring, as a matter of fact they pursue independent quantum-orbits and do not chase each other in the same orbit as might appear from the figure, which is to be regarded as purely diagrammatic. These independent orbits, circular or elliptic, may vary greatly in size but always have diameters related to that of the innermost, in the ratio 1, 4, 9, 16, etc., just as with hydrogen; and the electron-jumps from any outer to an inner orbit correspond to a definite emission of energy, the quanta giving, as might be expected, a rather more complex spectrum than that of hydrogen.

The next element, lithium (atomic number 3), has seven positive protons bound with four electrons in the nucleus, which thus has a net positive charge $(7-4)$ of 3, neutralised by three orbital electrons; and so on, until we reach the weightiest element, uranium. Here we have a nucleus of 238 protons with 146 nuclear electrons and a net positive charge therefore of 92 $(238-146)$, thus requiring ninety-two orbital electrons. *The number of free (orbital) electrons in all cases gives*

the atomic number of the element. The sequence of the atomic numbers of the elements was determined by the brilliant young physicist, Moseley (who lost his life in the Gallipoli campaign), by using X-rays in his researches (see Table, pp. 380, 381).

We have now got to the length of believing that the electron, the ultimate unit of negative electricity, when combined with a unit of positive electricity, forms matter (hydrogen), but what the unit of positive electricity (the proton) is we have as yet no more conception than we have of what the electron is. In an after-dinner speech one of our distinguished physicists, when asked to explain the difference between electricity and matter, replied that it was "immaterial," reminding us of the older definitions of mind and matter attributed to T. H. Key, once Head of University College School, "What is mind? No matter. What is matter? Never mind."

Electron Rings.—It is necessary now to consider how these orbital electrons are distributed in the atoms of the various elements, according to Bohr's theory, and how some of them may be detached; though it will not be possible, in a simple description such as is outlined here, to give the underlying physical and mathematical reasons for the distribution assigned. To simplify matters we will consider *neutral* atoms (*i.e.*, those with their full complement of orbital electrons) and leave out all questions of movements of the various electrons in their many circular and elliptical orbits. To this end we can conveniently regard the electrons as stationary. It is found that, as the atomic numbers of elements increase from 1 to 92, the electrons distribute themselves in a very definite manner, in the form of successive rings or shells surrounding the nucleus, as it increases in the elements of increasing atomic number from a mass (atomic weight) about 1 to about 238. Whilst the atom of helium has a simple ring of 2 electrons, the next higher atom, lithium (atomic number 3), has not got its 3 electrons in a similar ring of 3; it has 2 electrons like helium in an inner shell, while the third occupies an outer position or imaginary ring which is quite distinct. Moreover, this electron is relatively easily detached from the atom of lithium, and in this property of detachability it confers upon the element lithium many of its

characteristic chemical properties (ionisation). When we pass to the next higher element (beryllium), whose nucleus weighs about nine times as much as a proton and has 4 surrounding electrons (atomic number 4), we find again that only 2 are in the inner ring, while the other 2, which are more mobile, occupy the same kind of outer ring as that occupied by the outer lithium electron. And so on as we pass up the series of atomic numbers with increasing weight of nucleus, each additional electron finds a position in this outer or second ring, the inner one never having more than 2 electrons. Thus, taking the ascending series in succession, the next element, boron, has 3 such outer electrons, carbon 4, nitrogen 5, oxygen 6, fluorine 7, and neon 8. Up to fluorine, one or more of these outer-ring electrons are easily detachable from the atoms (conferring characteristic chemical properties by so doing), whilst the inner ring of 2 is stable and unaffected by chemical treatment.

Neon has atomic number 10 with a nucleus weighing about 20 protons, and when we pass to the next higher element we notice something very remarkable, which reminds us of the passage from helium to lithium. Sodium (atomic number 11) is this next element, but it is found that the extra electron it contains (as compared to neon) does not slip into the same second ring as with the previous series, but starts in a new outer ring of its own. This makes a total of 3 rings now—namely, the inner ring of 2, the second ring of 8, and the outer ring of 1. And as we continue passing up the series of elements by increasing the weight of the nucleus and adding one electron at a time, we find that "history repeats itself," so to speak; these additional electrons range themselves in this third ring, one by one, as we increase the atomic number step by step, and as before one or more of these outer ring-electrons are easily detachable and responsible for the chemical properties of the respective elements. But when a second octet ring (8) is completed the filling-in process stops—a ninth electron cannot be inserted in this third ring, any more than it could before with the second ring.

The atom whose third ring has 8 electrons is that of the element argon, and it is a most significant thing that helium,

neon, and argon, each of which has *completed* shells or rings of electrons (respectively 2, 8, and 8), that refuse to accept any more, are remarkably similar in being *inert* gases—that is to say, unlike the other elements, they refuse to enter into chemical combination with anything.

It would seem then as if chemical reactivity requires an uncompleted outer ring of more or less easily detachable electrons, and for this reason the outer rings of elements are called valency-rings, valency being, as we shall see later (p. 379), an expression of the saturation-capacity of an atom by other atoms, on chemical combination.

As we proceed higher up the series of elements, and the nucleus increases in weight, the case becomes more complicated and need not be followed here, except to say that with the formation of further outer rings, the completed shells or rings may have 18 and not 8 electrons.

So distinct and so fundamental to physics and chemistry are these successive electron-rings of the elements that they have been given the labels K-, L-, M-, N-, etc., to distinguish them. The K-ring is the innermost one of 2 electrons; the L-ring is the next outer one of 8 electrons, the M-ring the next outer one of 8 electrons, and so on. We speak, for instance, of light-radiation disturbing, say, the N-ring, of X-rays disturbing the K-ring, and of chemical reactions or high temperature disturbing the outermost ring, whichever it happens to be. Although this is perfectly easy to understand in terms of a simple static model, such as we have for the moment been considering, the problem becomes bewilderingly complex when account is taken of the high-speed movements in circular and elliptic orbits, each related to that of lowest energy by the respective diameters, 1, 4, 9, 16, etc.; especially when it is remembered that no two electrons can occupy the same orbit any more than two men can stand on the same rung of a ladder.

We can look at it something like this, taking the neon atom to illustrate: Its outer octet L-ring, when actual electronic movements are taken into account, resolves itself into 8 independent orbits of lowest energy for the un-excited atom, and its K-ring similarly resolves itself into 2 independent orbits of

still lower energy. Each of these independent 10 orbits, in their respective distributions of 2 and 8, may now, on exciting the atom, change to larger orbits (circular and elliptic) whose diameters are related to the orbits of lowest energy by the sequence 1, 4, 9, 16, etc. When any single electron drops back from any of the higher to any of the lower orbits, a single quantum of energy is emitted as radiation, but the whole radiation for the various quanta must necessarily be very complicated. This complication reveals itself in the spectral lines which enable the actual electron-jumps to be elucidated.

If the case is complex for an atom like neon containing only 2 rings (K and L), it will be readily understood that it is so complex for atoms of higher atomic number as to baffle complete disentanglement. Moreover, difficulties with the Bohr model have appeared in recent years, which are dealt with on p. 272.

Atomic Nuclei.—Leaving aside for the moment the orbital electrons of atoms, let us now consider more fully the nature of the nuclei, in which virtually the whole of the weights of atoms (atomic weights) resides. It has already been noted that these weights are approximately multiples of the weight of one proton, and this would seem to suggest that, just as Prout suggested long ago (1815), all atoms of matter are ultimately made up of hydrogen, whose atom consists of one proton. As we shall see later (p. 283), there is experimental evidence for this view as well as good theoretical grounds, and it only remains to explain why the atomic weights of all elements are not *exact* multiples of that of hydrogen (1) if the atoms of all matter are contrived out of protons, in steadily increasing numbers, by packing them together in the nuclei of these atoms. After the middle of last century Stas made a series of most extraordinarily accurate atomic weight determinations, in the hope of proving or disproving a whole number rule, showing the truth or otherwise of Prout's hypothesis. He clearly indicated that, while many elements approximated closely to a whole-number atomic weight if oxygen were taken as the standard at exactly 16, which means hydrogen would be 1·008 instead of exactly 1, there were other elements like chlorine which were

hopelessly out of it and nowhere near a whole number; and so Prout's hypothesis was abandoned.

But we now know that chlorine and the other elements whose atomic weights are not whole numbers are not "pure" elements. They are chance mixtures of two practically identical elements of different atomic weight, which are to all intents and purposes whole numbers on the basis of $O = 16$. Such "mixed" elements have nuclei of different masses, but these elements have the same chemical properties, so are virtually indistinguishable and inseparable from one another; and they are called *isotopes* (see p. 256). Many such isotopes are now known, and their discovery put an entirely different complexion on the problem, for it turned out that in every case each individual of any isotopic mixture had without exception an atomic weight which was practically a whole number, on the basis $O = 16$. Practically, but not quite. And now the small discrepancy, as well as the reason why the standard cannot be taken on the basis of $H = 1$, was at last run to earth. It is that there is a definite loss of mass, referred to by Aston under the name "packing fraction," when several protons are bound together with some electrons into the nucleus of an atom. The loss is greatest when 4 protons are packed together with 2 electrons to give the helium nucleus, as explained on p. 382.

So now Science has reached the rather startling conclusion, though in modified form, that Prout was right and that all matter of the Universe is ultimately made up of protons—*i.e.*, of the same stuff as hydrogen. It comes to this then, that the nucleus of any other atom is made up of a definite number of protons (each of unit weight on the basis $O = 16$) somehow bound together with a certain number of electrons. And the difference between the number of protons (each of which is an atom of positive electricity) and the number of binding-electrons (each of which is an atom of negative electricity), represents the *net charge* of the nucleus. This net electrical charge is always positive, because in every nucleus there are always more protons than electrons.

Let us illustrate by taking a concrete case, say sodium, for the sake of simplicity, because it is one of the "pure" elements.

The nucleus of the sodium atom contains 23 protons packed together with 12 electrons, which can be regarded as in some way cementing the whole structure together. The net positive charge on the nucleus is therefore 11 (*i.e.*, 23 − 12), and so the nucleus requires 11 orbital electrons (*i.e.*, 11 negative charges) to make the neutral atom. And the researches of Rutherford, as we shall see later (p. 281), indicate that the nucleus itself, of heavy atoms, has an orbital type of structure, in which protons probably revolve around a dense centre containing protons and electrons.

Ionisation.—We have seen (p. 250) that some of the outer-ring electrons of an atom may be more or less easily detached, provided that this outer ring is not one of the *completed* series, 2, 8, 8, etc., as in helium or neon. We may now enquire further into this phenomenon, which is known as ionisation and is very important, inasmuch as most chemical reactivity seems to depend on it. An atom which has lost one such electron has a single positive charge, like lithium, written Li^+; one which has lost two has two positive charges, like Ca^{++}, and so on. How are these electrons lost, and what are the ionised atoms like? The principal agency in detaching outer electrons, so far as Nature is concerned, is simply thermal energy, and in the sun or stars more and more electrons are detached as the temperature rises, from surface to interior. Some atoms (like calcium) are more easily ionised in this way than others, and as the spectra of elements depend to a large extent on the degree of ionisation, it will be seen that stellar spectra are a fairly accurate measure of surface temperatures of the stars and sun. At the ordinary temperatures prevailing on earth there is no such thermal ionisation; the atoms are not only complete with their full complement of electrons, but these atoms mostly combine with each other (or other atoms) to form the molecules of familiar matter. And in doing so it is evident that the outer ring or valency electrons must be in some way concerned, because it is only those atoms, whose outer electrons are easily detachable, that can enter into these combinations which we call chemical reaction (so helium and the other inert gases cannot do so because of their complete and stable rings, and so it

comes about that their atoms are the same as their molecules).

Nevertheless it is possible to detach electrons, under conditions obtaining on earth, by utilising any appropriate form of energy of sufficient potential. For instance, bombardment by other atoms (as we shall see, p. 277) will chip off electrons and ionise gases. Or, again, the rays of the sun striking molecules of oxygen and nitrogen in the air does a similar thing, knocking off electrons from the atoms in the molecules, which thus become ionised (positively charged), and the electrons may remain free or become attached to other molecules which become negatively charged. At night time when there is no sun, more or less neutralisation of these charged molecules occurs by the electrons being captured by atoms of molecules which had lost them.

Again, mere rubbing of the molecular surfaces of matter may detach electrons from the atoms of the molecules, leaving an excess of them on one of the rubbed surfaces, which thus becomes negatively charged, and a deficiency on the other surface, which becomes positively charged. This, of course, is the explanation of frictional or so-called "static" electricity (p. 134), and when a spark or lightning passes between objects of opposite charge it is due to a surge of electrons passing from the negatively charged to the positively charged object; whilst an electric current consists of a continuous flow of electrons (from – to +) along such materials as metals which pass them on freely from atom to atom (conductors). Thunderstorms, considered later (see p. 367), arise from the frictional detachment of electrons from the molecules of water-drops (which become +) by a rapid air current, the molecules of which become negatively charged.

Long before these things were clear and before J. J. Thomson had shown that the electron is the ubiquitous atom of negative electricity, chemists had been forced to the belief that certain types of compound, known as electrolytes, suffered dissociation into their ions (+ and –) when dissolved in water. Electrolytes in solution conduct electricity, not like metals unchanged, but in such a way that a positive ion is attracted to the negative electrode or pole (cathode) and a negative ion to the positive

electrode (anode); and, as we have seen (p. 157), it was Faraday who first made this great and fundamental discovery. The principal electrolytes are salts and acids, and, as we shall see later, they conduct electricity because in solution these substances do not merely dissolve unchanged like sugar, but actually break up into oppositely charged ions. When for instance common salt, NaCl, is dissolved in water the sodium atom parts with an electron of its outer valency ring, becoming the positively charged sodium ion (Na^+), whilst the chlorine atom picks up this electron and becomes the negatively charged chlorine ion (Cl^-). It is important to observe that the ions have quite different chemical characters from those of the neutral atoms; and, moreover, the chemical properties of the elements, as such, are largely due to the ease or difficulty with which they lose one or more valency electrons, passing into ions whose properties are quite different from those of the elements themselves. We will deal more fully with these matters when we come to consider the consequences of the theory of electrolytic dissociation (p. 378).

Isotopes.—We now return to isotopic elements. In Fig. 93, 6, potassium is represented as having 19 free electrons, giving the atomic number of 19, but, in 1920, Aston discovered that potassium had two kinds of atoms, one with the atomic weight 39 and the other with the atomic weight 41. Since the number of orbital electrons is the same in both forms of the element—viz., 19—it follows that the nucleus of one atom has 39 protons and 20 bound electrons, while the nucleus of the other has 41 protons and 22 bound electrons. It is important to observe that the *total* number of electrons—*i.e.*, those bound in the nucleus plus those freely moving in orbits—in any atom is equal to the total number of protons in the nucleus, and therefore is equal to the atomic mass (mass number). The latter is the same as the atomic weight in the case of "pure" elements like sodium, but not so in the case of potassium, some of whose atoms (the majority) have mass 39 and some (a minority) have mass 41. So it comes about that the element potassium, as presented to us by Nature, has an atomic weight between these figures—viz., 39·1. Many other elements—*e.g.*, lead (p. 354)—similarly are made up of two or more kinds of atoms differing

in weight, and to these the name *isotopes* (equal places) has been given, indicating that, though their atomic mass may differ, their chemical characters remain identical and they have the same atomic number (see p. 249).

To conclude, we may say that the modern explanation of the chemical affinity of atoms, in forming compounds, involves a redistribution of the outer-shell electrons of the combining elements. These outer electrons are the valency electrons, and Langmuir showed that there is a tendency for them to form groups of eight (octet theory) round the central atoms after combination. All recent work goes to demonstrate that the fundamental properties of an element are determined by (1) its valency electrons; (2) its total orbital electrons. The number of the latter is the *atomic number* of the element, and it is the atomic number rather than the atomic weight which is significant in the identity of an element. These free or orbital electrons increase from 1 (hydrogen) through a steady sequence to 92 (uranium), the element of highest atomic number—*i.e.*, while many isotopes appear no higher elements are known.

Radiation and the Quantum Theory.

The advances made in recent years into the fundamental nature of radiation have so utterly transformed the outlook of the physicist and philosopher since the so-called "classical" science of the nineteenth century, that some attempt must be made here to explain the new views which are so pregnant in meaning to the cosmogony of today. The simple diagram on p. 107 will help the reader to follow this explanation.

Anyone who warms himself before a glowing fire, or basks in the sun, is conscious through his senses of something (heat and light) which is conveyed across intervening space from the radiating object to his skin; that is to say, from a material which is radiating across nothing material (for air is not necessary but rather a hindrance) to some distant material (or perchance nothing). Such radiation (heat or light) is a mobile form of energy, for it can do work and can be measured accurately in terms of work. But other forms of radiation, also energy, not perceptible to the senses can be detected and measured by

scientific instruments, and a whole range of radiation has thus been disclosed, of which heat and light constitute a mere fraction. What is this radiant energy of such enormous range, and how does it travel across empty space, as, for example, from the sun, stars, and even more distant nebulæ? No all-satisfying answer has yet been found to these simple questions. We know that the rays from any radiating object spread out in all directions in virtually straight lines (in absence of material influence), and so their intensity must fall off with distance according to the law of inverse squares. For example, Venus is about ·7 times the earth's distance (taken as unity) from the sun; it will receive, therefore, about twice the radiant light and heat (for the ratio for Venus : Earth will be $\frac{1}{\cdot 7 \times \cdot 7} : \frac{1}{1 \times 1}$, that is, practically 2 : 1). We know also that *all* forms of radiant energy are electromagnetic manifestations (see p. 290) and travel with the same speed: cosmic rays, γ-rays, X-rays, ultra-violet rays, light-rays, heat-rays (infra-red), and radio-waves ("wireless") all travel at the same speed, 186,000 miles a second. This is one of the most fundamental constants of Nature; the constant C (velocity of light) comes into endless mathematical formulæ expressing the laws of science. We also know that unless the rays strike material atoms somewhere they remain intact, go on indefinitely and apparently for ever. So far so good. But what is the nature of radiant energy, how does it travel across space at this prodigious speed, and what becomes of it? These are questions which are more easily put than answered. Since the days of Huygens and Young (p. 114) the only satisfactory solution seemed to lie in the postulation of a "luminiferous ether," filling all space including that occupied by matter, this ether transmitting radiation by wave-motion; and it may be said that the whole of the nineteenth century occupied itself with the elaboration of this conception of light- and heat-transmission, in terms of waves of different lengths in an imaginary ether. The analogy with material wave transmission, as in water or as with sound, seemed so complete and the enormous success of the wave-theory so patent in explaining the multitudinous observations of physical science, that little

doubt was entertained of its fundamental truth. And later, since the end of the nineteenth century when shorter waves were discovered than those of light and heat, like X-rays, and longer ones like radio-waves, these discoveries fitted in so perfectly with the theory, by merely extending the length of the spectrum of radiation, that the undulatory theory *seemed* complete in its triumph. Just as with sound a whole range of octaves of waves are audible to the ear, conveyed by material vibrations, of definite oscillation-frequency for each note, so a much greater range of octaves of ethereal waves are detectable by human sense or scientific instruments, conveyed by non-material vibrations of definite oscillation-frequency for each effect. All the colours of light, for example, ranging from violet (higher frequency of vibration) to red (half the frequency), are thus comprised within one single octave out of the hundred or so octaves of ethereal vibrations thus believed to exist. Of these octaves 11 of very long wave-length (running into hundreds of yards) are used in "wireless" transmission (radio-waves); 17 octaves (from a fraction of an inch to about 14 yards) comprise the so-called Hertzian waves (p. 286); 9 octaves (from about 1 to 200 μ*) comprise the heat radiation of the "infra-red" region of the spectrum; and one octave (ranging from 8,000 to 4,000 Ångström units*) comprises the full spectrum of light, where 4,000 is the wave-length of violet and 8,000 red. On the other side of the scale, with still shorter wave-lengths we come to about 5 octaves of ultra-violet light (not visible to the eye) ranging from 4,000 to 136 Ångström units; beyond these about 9 octaves of X-rays and γ-rays of excessively short wave-length, down to ·06 Ångström unit, and far away beyond these come the so-called "cosmic rays" of wave-length in the neighbourhood of ·0002 Ångström unit.

Oscillation-Frequency.—A very important relation must be pointed out here—namely, that between wave-length and oscillation-frequency. This is best explained by considering the analogous case of sound. When middle C of the piano is

* An Ångström unit is a convenient one, largely used by science for small magnitudes. It is one hundred millionth of a centimetre (which itself is rather less than half an inch)—*i.e.*, one Å.U. = 10^{-8} cm. One $\mu = \frac{1}{10000}$ cm.

struck, if the piano is at concert pitch, the sound emitted is found to correspond to 256 complete vibrations per second; when C-octave is struck in the treble the vibrations are exactly double this—viz., 512 per second; and when C-octave in the bass is struck the vibrations are exactly half of middle C—viz., 128. That is to say, within any octave the vibration-frequencies may have all values between a given number and just double; and this applies equally to the range of frequencies of all the many octaves of ethereal vibration. From the longest waves to the shortest there is a continual increase in frequency, which doubles itself for each octave as the scale is descended. Thus the shorter the wave-length the higher the frequency. To understand this more clearly let us return to sound. The velocity of sound is independent of the wave-length or frequency—it is about 1,100 feet a second for ordinary air conditions, but varies with temperature and density. A moment's thought will make it clear that if a short wave of sound and a long one have got to travel at the same pace by oscillatory wave transmission, the short wave must oscillate more rapidly than the long wave to keep up. It is like a short-legged and long-legged pair of people walking together. If they are to keep the same pace either the short man must take quicker steps or the tall man slower steps, if each keeps to his natural stride-length. To put the matter in simple mathematical terms, the oscillation-frequency is inversely proportional to the wave-length, and if the velocity is known we can say for all cases:

$$F = \frac{V}{W}$$

where F is the frequency of vibration, V is the velocity, and W is the wave-length, whose reciprocal is the *wave-number*. Applying this to so-called ethereal vibrations it is easy to see how, since V and W are known with accuracy for all points of the scale, the frequencies can always be calculated. It will also be easily seen that the frequency is quite small for B.B.C. radio-waves—namely, of the order of a few hundred thousand per second; larger (hundreds of millions to a million million) for short Hertzian waves; about 100 million million for heat-waves; still greater for light waves; of the order 1 to 30 million million

million for X-rays and γ-rays; and inconceivably rapid for cosmic rays. The figures for these oscillation-frequencies (*i.e.*, beats to the second) convey nothing to the human mind; they are too big, but they are of transcendent importance in mathematical analysis. And whether the undulatory theory, which involves these figures, be true or whether, as later discoveries seem to indicate, it is merely a convenient device, Science cannot dispense with waves and oscillation-frequencies. The present position of physics is in a sense a contradictory one, inasmuch as it requires the undulatory theory on the one hand, as well as a modification of Newton's corpuscular theory on the other, to explain the facts. The theory, known as the quantum theory (see p. 264), discards the ether as unnecessary, and it is just this contradiction which makes it impossible to say as yet what radiant energy really is or how it travels. The quantum theory, first developed by Planck, is necessary simply because the new facts of the twentieth century could not be adequately explained by the undulatory theory.

In order to follow the quantum theory and its more recent developments it is necessary to refer first to matter as a radiant source of energy and to the dimensions of material particles.

Matter, as we have seen, may be analysed into ultimate units. Masses within the range of our eyesight may, with the aid of the best microscopes, be seen to be composed of particles as small as 0·2 μ in diameter ($\mu = \frac{1}{1000}$ mm.); these particles are in turn composed of molecules whose diameters lie somewhere between 0·1 and 0·5 $\mu\mu$ ($\mu\mu = \frac{1}{1000000}$ mm.); molecules, again, are composed of atoms which themselves are constructed out of vastly smaller protons and electrons, and there our analysis stops. And radiation has been traced to the oscillatory movements of these protons, electrons, atoms, or molecules, as we shall see.

Heat Radiation.—Even when matter is only warm it is in a condition to radiate. The surface of any material object is radiating when it is what we call cold, even excessively cold, so long as the temperature is above absolute zero (−273° C.)—*i.e.*, it is losing radiant energy and therefore getting colder, provided that it is not receiving heat, say, from some other

radiating surface. The hot atoms or molecules vibrate as we have seen (pp. 229, 230), and the point to bear in mind is that these vibrations set up oscillatory waves, which pass out as radiation (heat) into space—*i.e.*, energy, which is lost. It is something like a vibrating tuning-fork sending out sound waves into the air (a rather crude parallel); and so any material object, in the absence of other material radiating objects near or distant, will lose any heat it possesses by radiating its energy into space. It would, in fact, ultimately cool down to a temperature of absolute zero, where there is no longer any heat energy. This radiation is from the surface, but as heat is conducted from within to the surface the whole material object cools down, as a red-hot poker cools. The latter does not cool down to absolute zero, because its surroundings supply it with heat long before this, partly by radiation and partly by conduction and convection. Its final temperature, if the poker were in a vacuum so as to exclude the complication of conduction, would be that temperature of equilibrium at which it radiated out exactly the same amount of heat energy as it receives by radiation from its surroundings.

Now if we examine this heat radiation emitted by any familiar cold (or warm) object, or say by a red-hot poker, we find that it does not consist of a single wave-length—*i.e.*, definite oscillation-frequency—but of a whole range of frequencies, and if we further examine the energy of radiation over this long range we find that it shows a decided maximum at a certain position in the range (spectrum), this position being determined solely by the temperature of the radiating object.

For example, imagine a sheet of ice on a frozen pond radiating energy to a clear night sky. The temperature is 0° C., and so long as there is water beneath, it will remain at 0° C. The *maximum* energy of the range for this temperature is found to have a wave-length of about 11 μ. For a red-hot poker the maximum energy point, in the range of radiation, is found to be at about 6 μ, and for an intensely (white) hot furnace, about 3 μ. This important relation between maximum energy and temperature of the radiating object is known as Wien's displacement law, which states that the wave-length of the radia-

tion at the point of maximum energy is inversely proportional to the *absolute* temperature. To take a well-known illustration of this law, consider the case of the sun. The sun's radiation covers an enormous range, but only about 5 octaves penetrate through the earth's atmosphere—namely, nearly an octave of invisible ultra-violet light, 1 octave of visible light, and about 4 octaves of infra-red, the so-called invisible heat-rays. All these octaves of radiation on absorption by matter on the earth give heat among other forms of energy, so that it is quite a mistake to suppose that the heat-rays are confined to the infra-red; they are merely the invisible heat rays which give up their energy mainly as heat. But in this long range of solar radiation much the strongest or most energetic point is found to be at a wave-length of $\cdot 5\ \mu$ (blue light), from which by Wien's law it can be calculated that the sun's surface temperature must be about 6,000° C. In the same way it is possible to calculate the surface temperature of the stars.

Another important point to bear in mind is that not only does the wave-length of maximum energy, from any radiating object, diminish as the temperature rises (*i.e.*, the oscillation-frequency increases), but the amount of maximum energy increases steeply as the temperature rises; and the total amount of energy of all the radiation also increases rapidly with increase of temperature. That is why cool objects do not appear to be radiating at all and why a brightly burning coal fire gives out so much more radiant heat than one barely red-hot. In fact, Stefan showed that the total energy of emission is proportional to the fourth power of the absolute temperature (T^4).

Strictly speaking, the above observations on the relation between quality or quantity of radiation and temperature are true only of perfect radiators—the so-called black body radiation like carbon black. The actual radiation from the atoms and molecules of matter really consists of a vast number of spectral lines and bands jumbled together, so as to appear practically as a "continuous spectrum." It is just as if with a piano some clumsy player jumbled more or less all the notes together instead of playing a melody by striking pure notes or harmonies. It is just this melody of pure notes which the

atoms of single elements play (as it were) when stimulated by heat, and it is the business of the physicist to disentangle out these pure notes and harmonies as spectral lines, when he examines experimentally and mathematically the radiation emitted by pure substances. In Nature, substances are not usually pure atoms but inextricably mixed atoms and molecules, and so the radiation emitted by most forms of matter is the jumble of lines and bands which constitute a more or less continuous spectrum (p. 162).

While studying the amount of energy in different parts of the spectrum of radiant heat Professor Max Planck of Berlin University, in 1900, was forced to the conclusion that the energy given out must be regarded as made up of separate units or "packets," the size of each packet, or "quantum" as he called it, depending on the oscillation frequency of the radiation, in the particular part of the spectrum under consideration. Heat might, therefore, be radiated off in an exact number of quanta, but fractions of a quantum were impossible. The quantum is thus equal to a constant value ("Planck's constant") multiplied by the number of wave-oscillations per second—*i.e.*, by the frequency. Exactly what the mechanism of the action was Planck was unable to say, and it was not until Bohr introduced the conception into his theory of the structure of the atom that it became possible to visualise what was taking place.

When it had become quite impossible to reconcile the behaviour of the electrons in regard to the production of waves with the "classical" theory, Bohr showed mathematically that if the electrons in the atom were assumed to revolve at enormous speed in definite orbits, the change in energy by the electron jumping from any one orbit to any other fitted in exactly with Planck's theory, and also explained why the spectrum of any element had definite lines in mathematical sequence. The position of any line in the spectrum corresponds to the energy given out by any electron falling from an outer to an inner orbit, and the total number of lines corresponds to the various combinations of jumps which are possible between the several orbits. The orbits themselves are spaced at distances from the nucleus following a definite sequence (p. 247), and the eccentricity or ellipticity

follows a definite sequence, all dependent on the degree of excitation (temperature) of the atom, as we have seen. Moreover, the lines in such a spectrum are themselves composed of finer lines very close together, and Sommerfeld has explained them mathematically by means of Einstein's theory, which demands that the mass of a body, in this case an electron, must change with varying velocities (p. 295). Not only so, but an intelligible conception of the nature of X-rays now becomes possible, for these are due to the displacement of the electrons in the orbits nearest to the nucleus.

Absorption of Radiation.—When radiation quanta from any object meet matter which obstructs them they shake up the atoms and molecules of this matter, in such a way that, either the atoms and molecules are set in some vibratory or rotatory condition, or the electron-components of the atoms themselves are disturbed. A rough sort of analogy is a ship agitated by the waves of the sea, where there is some sort of relation between the length of the waves (distance from crest to crest) and the length of the ship. This kind of relation between wave-length and size of object involved is a very marked feature of the radiation we are considering, the so-called ethereal waves. It can be proved mathematically, and it has been demonstrated experimentally, that any electrical structure like an atom will only be disturbed by radiation, the wave-length of which is nearly a thousand times the dimensions of the structure (to be precise, 860 times). Only when the wave-length is below this limit will the structure be affected and the radiation be absorbed as definite quanta of energy, by doing the work of agitation.

Let us take some examples to illustrate this fundamental principle. Suppose we take a homogeneous pencil of rays of pure wave-length 3 μ (*i.e.*, in the infra-red) analogous to a pure single note of sound, and allow these rays to strike a sheet of cold water. We find that these rays are *entirely* absorbed by the water, which is warmed in the process; the electrons of the atoms (hydrogen and oxygen) of water are not in the least affected, because the diameters of the electron orbits are far below $\frac{1}{860}$ of 3 μ in dimensions, but the molecules themselves

are just about these dimensions. These are put into a condition of increased oscillation and rotation about their centres of gravity, and this manifests itself in a rise of temperature.

Glass, having larger molecules than water and of different shape, is transparent to infra-red and light radiations, so long as the wave-lengths are below about 3 μ and the glass is not too thick, but it absorbs wave-lengths of 5-6 μ. When the sun's rays, which are rich in all these wave-lengths, pass through glass those not absorbed will be still capable of warming water and other materials able to absorb them. The temperature of such objects so warmed, say to 20° C., will emit radiations mainly consisting of much greater wave-length (maximum at about 10 μ), as explained under Wien's law (see p. 262), and, as glass is largely opaque to these wave-lengths, these radiations are mainly absorbed by the glass. This explains why it is that the heat is trapped, as it were, in a greenhouse or garden frame—it is not merely that the sun heats the interior directly, but that this heat cannot freely escape to space by radiation, quite apart from any losses of heat by conduction or convection. If the glass is coloured, say blue, this means that there are molecules present (cobalt in this case) which are agitated by, and so absorb, certain wave-lengths, like red, of the visible octave of light, the energy of these absorbed rays being transformed into heat. It should be noted here that ordinary glass has molecules of such sizes and shapes that, while transparent to white light, it is opaque to ultra-violet light, and as the health-bestowing properties of sunlight depend upon all its rays, sunlight is to a great extent deficient in these properties if the ultra-violet rays are cut out, whether by glass or by a smoky atmosphere. The newly invented Vita-glass lets through these valuable ultra-violet rays, and it is therefore good for windows provided they are kept very clean, but unfortunately after a while some Vita-glass gradually loses this special transparency to ultra-violet rays.

Now, imagine the case of the human eye, and let the wave-length of the radiation be changed to, say, ·8 μ. It is now pure (monochromatic) red light, and when it strikes the eye it is found to disturb the atomic orbits of electrons of dimensions $\frac{1}{800}$ of

·8 μ, but not those below this limit. It is the disturbance of the electron orbits of the atoms of sensitive chemical compounds in the retina of the eye that makes ordinary light visible to us; and because the orbits of the electrons of silver atoms are not disturbed by red light (·8 μ), but are agitated by blue light of half this wave-length (and below), the photographic plate is similarly affected.

For similar reasons X-rays (of very short wave-length) have a much more devastating effect on the atoms of matter, since they go, as it were, deep down into the atom and disturb the inner K- and L-rings (p. 251), whilst light only agitates the outer electrons. γ-Rays even affect the nucleus of atoms, and cosmic rays in some way appear to affect the proton itself, though this is insufficiently understood at present.

All this applies to the *absorption* of radiation by the atoms and molecules of matter, but the exact converse is no less equally true. That is to say, when any atom or molecule is agitated it will radiate energy of just that wave-length (or set of wave-lengths) which corresponds to the degree of disturbance. If the molecules only are agitated radiant heat (various infra-red rays) only will be emitted. This happens when the temperature rises from $-273°$ C. upwards, but as the temperature rises and the electrons begin to be stirred at about 400° C. shorter waves will also appear and the object will show the appearance light (incipient red heat). At still higher temperatures the electron agitation increases so much as to give most of the rays of the octave of visible white light, and the total energy of radiation, as we have seen, greatly increases. At the temperature of the sun's surface (6,000° C.) still shorter waves appear as the inner electrons begin to be disturbed. At temperatures ranging from 115,000° to 29,000,000° C., such as are found within the sun, the innermost K- and L-rings are agitated with production of the excessively short wave-length X-rays. At the still higher temperatures of the interior of dense stars (up to several hundred million degrees C.), the nuclei themselves of the atoms are disturbed and γ-rays appear. Lastly, cosmic rays, which may arise from the actual annihilation of protons and electrons, correspond to the unthinkable

temperature of over 2 million million degrees C., and this hypothesis of annihilation is supported by the fact that the wave lengths of these cosmic rays are about 860 times the dimensions of protons. It would seem then that the limit of radiant energy is reached when the disturbance actually causes the destruction of matter itself (see p. 269).

Mass and Energy.—To make this problem clearer it is necessary to explain more fully what a quantum really is. Let us take a single packet of energy, the quantum, and examine it. It is the amount of energy, measurable but extremely minute, which is emitted as radiation when a single electron falls from a given outer orbit to an inner orbit (see p. 252). Its energy is found to be strictly proportional, as we have seen, to the oscillation-frequency and to a constant (h, known as Planck's constant) which appears to be one of the fundamental constants of Nature. So it is obvious that the energy of any single packet or quantum must be relatively small for radiation of long wave-length (like infra-red rays), much greater for light and ultra-violet light, relatively enormous for X-rays and still more so for γ-rays. Now, as will be seen later (p. 295) in dealing with Relativity, energy and matter are, strictly speaking, interchangeable terms in the last analysis of the problem. It is true we are not able to convert matter into energy or vice versa to any measurable extent in any laboratory process, but it can be demonstrated theoretically that such change is not only possible, but that it probably occurs on a stupendous scale in the sun and stars. This is tantamount to saying that after all matter is not indestructible, and that another of the most cherished beliefs of the nineteenth century has been shattered. The real truth appears to be that, so far as ordinary experience on this earth is concerned, matter undergoes *no appreciable* change of mass in any chemical transformations it may suffer, but that the law of conservation of mass and energy must be modified to mean that a kind of sum of these two is indestructible, and that matter can be transformed into energy, in short, annihilated so far as atomic constitution is concerned. Conversely we can now definitely say that energy has mass, just as matter has, small though

this mass is. It has been calculated exactly what a definite amount of energy must weigh, and vice versa it has been calculated what is the amount of energy which would be released by the annihilation of 1 gram of matter (p. 296). The latter is something prodigious and would, if it were ever possible to utilise it, do the work of thousands of tons of burning coal.

Cosmic Rays.—To return to cosmic rays, since the wave-length of these has been determined and so the oscillation-frequency found, the energy of each quantum of these rays can be calculated. When this energy is now expressed as its equivalent in mass the surprising result is obtained of almost exactly the weight of one single proton. This, then, would seem to confirm the belief (put forward by Sir James Jeans) that these cosmic rays arise from the actual annihilation of matter (protons) with liberation of the equivalent amount of energy; and, as might be imagined, this energy is at higher potential than any other form of energy in the universe.

These cosmic rays, especially associated with the name of Millikan, are entitled to the epithet cosmic because they literally pour in upon the earth from the whole universe, and not from the sun and stars. They have enormous powers of penetration, far exceeding X-rays or even γ-rays, and can pierce through many feet of solid lead. According to Jeans, they come from the 2 million or so extra-galactic nebulæ, which are found within the confines of the known universe, and they originate in these nebulæ by the actual annihilation of matter. Other theories ascribe these rays to the creation of matter in cold regions of the universe, but there are difficulties in the way of accepting these views. As Jeans supposes that annihilation of matter is the source of radiant energy of all stars, including the sun and nebulæ, it remains to be explained why these rays do not come from the sun and stars more than from any other region of the sky. To understand this it is necessary to refer to phenomena recently discovered and known as the Compton and the Raman effects. When radiation of any kind, in its journey through space whether long or short, strikes an atom or molecule several things might happen. The radiation might go on undisturbed, as with transparent substances; it might be reflected,

with polarisation (p. 117); or it might be absorbed, more or less giving effects which have already been described. It might also be *scattered*, and it is in connection with scattering that the Compton effect has been observed.

In 1923 Compton showed that when an X-ray collides with an electron there is true scattering, and the X-ray behaves as if it were a material particle, giving an elastic collision, with a measurable recoil of the electron. So striking is this effect, that we may say that the rays behave as if they were discrete particles, in spite of the fact that, like other forms of radiation, they show the usual " interference " and " polarisation " associated with waves. Indeed, these observations make it more difficult than ever to reconcile the manifestly corpuscular nature of light with the undulatory theory. It amounts to this, then, that the present-day position of physics is paradoxical, in the sense that physicists cannot get on without both of these apparently opposed theories.

It has long been known that ordinary light radiation exerted pressure upon any blackened object capable of absorbing the rays, and the familiar toy called the radiometer, invented by Crookes in 1874, shows this beautifully; within the vacuum tube the little vane of four discs, each blackened on one side, rotates merrily when the sun shines, because of this pressure. Radiation pressure becomes a very important thing in the stars, as Eddington has shown; indeed, when the temperature is very high, it is so great as to rival the pressure (gas pressure or kinetic energy, due to temperature) of the atoms themselves; and so it is partly responsible for maintaining some stars in a distended condition of immense gas balloons without collapsing. In the light of the quantum theory, we are now better able to understand both radiation pressure and scattering. These phenomena force us to believe that the quantum is virtually a third fundamental unit of matter, which differs from the other two (proton and electron) by possessing no charge, but merely an electric field, a mass varying with the wave-length (for ordinary light only about ·000005 that of the electron), and a velocity equal to that of light. This hypothetical unit is sometimes called the *photon*,

and the essential fact, upon which its existence is postulated, is that when it is scattered by striking electrons, part of the scattered quantum has less than its original energy—*i.e.*, there is a decrease in the oscillation-frequency.

Scattering in fact differs from reflection by the fact that the scattered quanta are only partly the original ones; some of the radiation scattered has a higher frequency than the original and some (more) a lower frequency, and with light radiation the difference between the two latter frequencies is found to be the characteristic frequency of the substance in its heat (infra-red) radiation. This is the Raman effect, and the general result is to "soften" (as physicists say) the radiation—*i.e.*, to enrich the radiation with lower frequency quanta at the expense of higher frequency. A whitewashed wall which scatters (as well as reflects and absorbs) sunlight may be intolerably hot in summer because of the enriched infra-red radiation produced by the scattering. This "softening" result is known as the Compton effect, and it will be readily understood that if highly penetrating radiation, like cosmic-rays and γ-rays, or even X-rays, are generated within the interior of the sun or a star, these rays will be so "softened" by scattering in their long journey to the surface, by encountering such multitudes of atoms on their way, that the final radiation appearing at the surface will be indistinguishable from ordinary temperature radiation (Jeans).

Very different is the case with the transparent nebulæ. These are so thinly packed with atoms that their densities are lower by thousands of times than the most extreme vacua attainable by any laboratory vacuum pump. The nebulæ, except towards their centres, are in a condition of extreme tenuity, and so scattering will be comparatively slight; and highly penetrating radiation from within can get out and across the universe without much softening. This theory of Jeans is of great importance in its relation to cosmogony, and it is confirmed not only by mathematical handling of the quantum theory but also by observational means, since the intensity of cosmic rays appears to be greatest in the direction of the nearer nebulæ such as that in the constellation of Andromeda.

The original quantum theory of Planck and the Bohr model of atomic structure, which promised so well, are not perfectly in accord with certain experimental observations of spectral lines, and physicists have now begun to doubt whether the electrons of an atom can be regarded as real particles, performing similar functions in space to those of macroscopic or gross material particles. Electrons are altogether too elusive and evasive to be susceptible to the same kind of experimental enquiry as, say, the planets circling round the sun or even atoms; and Heisenberg, who has founded the new quantum theory, would go so far as to say that (as Eddington puts it) "a particle may have position or it may have velocity, but it cannot in any exact sense have both." The nature of the electron at present is very much in the melting-pot.

New Quantum Theory.—We saw on p. 248 that the same orbit cannot be occupied by 2 electons. It is as if each electron instead of being a material point somehow spread itself out so as to occupy an entire orbit to itself. With the higher, *i.e.* outer, orbits it is perfectly true that an electron behaves normally as a material point of definite mass and of velocity which may be determined; but at lowest energy when the electron drops into orbits which are relatively near the nucleus this definiteness gradually disappears and indeterminateness appears in its place. It now becomes impossible to identify the point or actual position of the electron in its orbit.

This puzzling feature is very disturbing to Science, which in the past has prided itself upon the objective accuracy of its determinations and freedom from subjective hallucination. So a new theory of wave-mechanics is groping its way in the attempt to understand the problem, but thus far it has only demonstrated that an electron at lowest energy is not like a material particle occupying a definite position in space.

The new quantum theory of Heisenberg (1925), extended by Dirac and Schrödinger, involves a recondite mathematical system of wave mechanics so abstruse as to be quite beyond the scope of this book. In this new system, as postulated by Schrödinger, an electron is really a sort of storm centre of waves or ripples in an imaginary sub-ether, such waves travelling

with speeds (not uniform like ether waves) depending on their wave-length (much in the same way as water ripples), and modified by mass influence, such as the nucleus of the atom. Elaborate calculations based on this new method give correct results for all the spectral lines, including those which are in error (p. 272) by the Bohr method, and the new theory promises to be extraordinarily fruitful. But it takes us to a world of shadows so abstract as to outbid even the theory of relativity (see p. 289), so that it is impossible to form any mental picture or model of what is really happening. Indeed, the further science probes into the hidden recesses of the atomic world, the more obscure and shadowy does objective reality seem, the less material and tangible does Nature appear to be. As Eddington says truly: "An addition to knowledge is won at the expense of an addition to ignorance. It is hard to empty the well of Truth with a leaky bucket."

Radioactivity.—Perhaps the most startling event in physics during recent years has been the discovery of the wonderful element, radium. In 1895, the French physicist, Henri Becquerel, found that a preparation of uranium, whose atom is the heaviest known, gave off something that could pass through black paper and even thin sheets of metal, and act on photographic plates, even when these were kept in the dark. This radiation had other remarkable properties; it had the power of causing certain substances to give off a phosphorescent glow; it generated heat, and had the power of making gases conductors of electricity.

Uranium is a hard white metal, which melts at about 1,600° C. It was discovered in 1789, and isolated in 1842 by Klaproth, professor of chemistry in Berlin, who also discovered strontium, zirconium, tellurium, and other rare metals. Uranium occurs in the mineral pitchblende, found in Cornwall, Norway and the United States, but especially in Joachimsthal in Czecho-Slovakia. All the compounds of uranium are "radioactive," but the real nature of this extraordinary substance was first elucidated by Professor and Madame Curie in 1898, when they discovered radium itself. After the accidental death of her husband in 1906, Madame Curie, a Pole by birth,

succeeded him as professor of physics at the Sorbonne in Paris, but, after the war, became professor of radiology at Warsaw.

Madame Curie's first discovery was that another element, called thorium, discovered by Berzelius in 1828, possessed radioactive properties like uranium. This element figures in the manufacture of Welsbach gas-mantles, although the incandescence of the mantle has no connection with radioactivity. Madame Curie also found that certain minerals containing uranium salts were much more radioactive than could be accounted for by the amount of uranium present in them. One of these minerals was pitchblende, and after prolonged labour she managed to extract from it the metallic elements bismuth and barium, which, although not themselves radioactive, were each associated with a new metallic element. One of these similar to bismuth was christened "polonium" by Madame Curie, in honour of her native country, Poland; the other was "radium," which was similar in many properties to barium. The radium was present in extremely small quantities, for it was estimated that not more than an ounce of radium could be obtained from 100 to 200 tons of the very richest variety of pitchblende—*i.e.*, one part in about 7 millions. Even before the war, radium bromide cost £15 to £20 per milligramme—*i.e.*, about $\frac{1}{70}$ of a grain.

The first remarkable fact which appeared was that radium gives out energy spontaneously, without appreciably altering or wasting away; this emission of energy can neither be controlled nor prevented. It has been calculated that a gram of metallic radium gives off 100 calories every hour, or about 100 thousand million calories during its lifetime! Here we might have one of the sources of the sun's energy, and we will later (p. 351) appreciate the vast importance of the radioactivity of the rocks when we come to consider modern geology. Since the days of Helmholtz and Kelvin science had regarded the law of conservation of energy (p. 127) as fundamental, for, as Professor Soddy says: "Energy can only be used once, nothing goes by itself"; but radium, about 1900, appeared as something exceptional.

Some idea of the nature of this "miraculum naturæ" may

be obtained by examining a very interesting little instrument invented by Sir William Crookes, and called by him a "spinthariscope," from the Greek word meaning a spark or star (Fig. 94). It consists of a small brass cylinder, B, having a film of zinc sulphide painted on the bottom, Z. This substance becomes luminous or phosphorescent when rays from a radioactive source impinge on it. A short distance above the zinc sulphide there is an adjustable needle, N, the tip of which has been merely rubbed against a tube that had contained a minute quantity of radium bromide so that the amount of radium on the needle must be, in the true sense of the word, quite infinitesimal. Fitting into the outer cylinder is an inner one carrying a lens, L. If the zinc sulphide film be examined through the lens in a dark room, it will be seen to glow, and when the eye becomes accustomed to the conditions the glow resolves itself into innumerable tiny sparks "like a shower of meteors on a winter night."

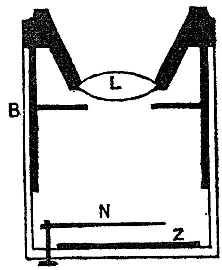


FIG. 94.—SPINTHARISCOPE.

These sparks are due to the battering of the so-called α-rays (Alpha rays) given off by the radium, each spark caused by the disruption of a particle of zinc sulphide when struck by an α-ray. After some months the glow becomes feebler, but this diminution is not owing to any loss of power on the part of the radium, but literally to the wearing away of the zinc sulphide by the perpetual bombardment to which it is subjected. If the film be renewed the meteoric display becomes as brilliant as ever. The radium may be said never to wear out—at least, the particle which the needle carries is estimated to last 2,000 years!

The question at once arises, What is it that is shot off, and what happens to the radium atoms so disintegrating?

Much information relating to radioactive problems has been acquired by employing the knowledge we have gained by the study of ionisation of gases. If the ends of an insulated glass tube containing a gas be connected with the terminals of a battery, the electric current does not pass through the gas; but if the tube is exposed to α-rays, the current at once begins

to flow. The reason is that the α-rays have the power, so to speak, of knocking off electrons from the atoms of the gas, resulting in the formation of particles of two kinds: (1) negative charges or electrons on the one hand, and (2) the remainder of the atom or molecule, positively charged, on the other. These particles are of course "ions" (see p. 254), and the gas is said to be "ionised." The degree of ionisation can be measured by the instrument called an electroscope, such as that devised by Professor C. T. R. Wilson of Cambridge (Fig. 95). The substance under examination is placed on the platform, A. Above it is a metal plate, B, continuous with a rod, C, held in a vertical position by the bar, H, which rests on the insulators, I, I. Attached to the top of C is a strip of gold leaf, G, which lies vertically but stands out (as shown) by repulsion when charged. At the top of the enclosing box is a wire, D, which may be depressed through the insulating block, F, by a spring knob, E, connected with a source of electricity. When E is depressed and D momentarily touches the top of C, the gold leaf becomes charged and stands out, and if the material on A be radioactive—*i.e.*, capable of inducing ionisation of the gas between A and B—the gold leaf falls back at a rate which may be measured against a scale which has been previously calibrated. The rate of fall of the gold leaf indicates the rate of leakage of the charge, and this gives the degree of conductivity of the gas or its ionisation.

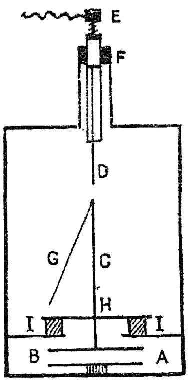


FIG. 95.—ELECTROSCOPE.

By placing films of various materials over the radioactive substance the penetrating power of the radiations may be determined. In this way it has been found that radioactive elements may give off "rays" of three kinds called α, β and γ. The α-rays are easily stopped by a sheet of paper, but β- and γ- (Beta and Gamma) rays pass through. A thin sheet of aluminium will, however, shut off the β-rays, but it requires a layer of metal several centimetres thick to block the γ-rays.

The α-rays are relatively massive, being in fact positively

charged particles, which have been shown to be atoms of helium that have lost their two orbital electrons. They move at a prodigious speed, estimated at 10,000 miles a second. They thus possess enormous energy, and it is to them that the flashes given off by the zinc sulphide in the spinthariscope are attributed. It is almost inconceivable that it should be possible to photograph the pathway of an object moving at such a speed, but it has been done by Professor C. T. R. Wilson in the following ingenious way.

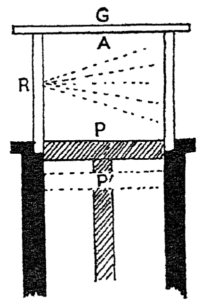


FIG. 96.—PHOTOGRAPHY OF α-RAYS. (WILSON.)

A cannon-ball fired through a field of wheat leaves a track behind it which is clearly recognisable, although the ball itself cannot be seen during its flight. Similarly an α-particle, moving several thousand times as fast, may be made to leave behind it a track revealing the path it has followed. We know only too well that fog is due to the condensation of moisture on particles of dust, soot, etc., in the air, and Wilson took advantage of this knowledge in devising his apparatus, the general principle of which is indicated in Fig. 96. The box A with a glass roof, G, has fixed on one side, at R, a minute speck of radioactive matter, which shoots its rays against the opposite wall. The floor of the box is formed by a piston, P, which can be lowered into the position P′. The air in the box is saturated with moisture, and when the piston is suddenly pulled down the air expands and is thus cooled, and cannot carry so much moisture. The excess is deposited as a miniature fog on the gaseous ions produced by the passage of the α-particles, and the path of the ray is thus defined by the chain of microscopic drops formed on the ions of the gas acting as condensation-nuclei.

This experimental technique, devised by Wilson, has proved to be extraordinarily fertile in the elucidation of the once mysterious phenomena of radioactivity. It has enabled the tracks and velocities of α- and β-particles to be photographed and determined, not only from radium, but from

numerous other radioactive elements; indeed, the method lies at the root of Rutherford's classic investigations.

The β-rays are light negatively charged particles which have been shown to consist of electrons, travelling with a speed comparable with that of light, while the γ-rays (Gamma) consist of true radiation (ethereal) like heat, light, or X-rays (travelling at the same speed) but of wave-length (p. 259) shorter even than X-rays, and consequently they have by far the greatest penetrating power. It will be seen, therefore, that only the γ-rays are rays in the ordinary sense of the word, since the α-rays and β-rays are truly material particles (ionised helium and electrons respectively) shot out with high speed.

The intensive study of radium and other radioactive elements, during the last thirty years, has thrown a flood of light upon the inner constitution of the atoms of matter; indeed it is principally owing to the researches of Rutherford on the spontaneous disintegration of radioactive elements that we have been able to penetrate so deeply into this problem. This disintegration is, so far as we know, confined practically to elements of high atomic number (84 to 92) with the exception of potassium, which is feebly radioactive; but it is thinkable that all the elements above hydrogen may disintegrate given a long enough time, and that such radioactivity is too feeble to be detected. It is significant that the weightier atoms are more unstable than the lighter ones, but it must be observed that instability is by no means a matter merely of the mass of the nucleus. Among the radioactive elements some with smaller mass have a shorter life than others with a larger mass. There must be something in the inner constitution of the nucleus itself that contributes to instability, for the life of some of these elements is so short as to be only a fraction of a second, whilst others of not very different mass have lives of the order of thousands of millions of years. Radium itself stands about midway between these extremes, and its life may be judged from the fact that about half of it changes into something else within 1,690 years.

Transmutation.—And what becomes of these unstable elements when they disintegrate? Many of them lose a charged atom of helium (α-particle), some lose only an electron (β-

particle), but in either case by so doing each changes into another unstable element which in its turn may lose helium or an electron, and so on, step by step, till the process stops at what we call a stable element, like lead. It will be, therefore, readily understood that, since the lives of the intermediate unstable elements are variable, the result got from any pure radioactive element at the start will be, after a time, a mixture of several other elements in addition to the original one, all in steady process of decay according to their respective lives, whether long or short. For example, if a piece of pure metallic radium were put in a closed empty vacuum tube, two gases slowly accumulate in the tube: one is helium, the atoms of which are ejected as high-speed α-particles (from the nucleus of some of the radium atoms); the other is the element niton or radon, which is the residue of the disintegrated radium atoms. This is proved by the fact that the atomic weight of niton is 222—*i.e.*, just 4 units less than that of its parent radium (226), these 4 units representing the mass of the helium atom ejected. The latter is flung out as the simple nucleus of its atom—*i.e.*, without the 2 electrons of the K-ring—and so it is positively charged; but it soon picks up stray electrons which are always available (p. 276) when it strikes other atoms of matter, and so it soon becomes ordinary helium, which can be identified by its properties. On the other hand, the residue, niton, of the disrupted atom of radium, must contain 2 electrons less than the latter, for it must be remembered that the nucleus of the helium atom has 2 embedded electrons in it (see p. 248). This deficiency of 2 electrons brings down the total orbital electrons by 2 and so reduces the atomic number by 2. In fact, niton has an atomic number of 86, whereas radium is 88. It must have a completed outer ring of electrons because it is one of the inert gases like helium itself, though a very different kind of gas.

Niton was at first called radium-emanation, because the investigators, Rutherford, Ramsay, and others, could not understand it. It was liquefied at a very low temperature, giving out a brilliant steel-blue light, and for that reason was named by Ramsay niton or "the shining one." Its true nature only gradually appeared, and then it transpired that this

remarkable gas was a new element of very short life (half-life period only about 4 days), going through a sequence of mostly very rapid successive transformations into a series of unstable elements which were metals. The sequence and periods of half-decay (complete change always takes a theoretically infinite time) are given below:

Niton ⟶ Radium-A ⟶ Radium-B ⟶ Radium-C ⟶ Radium-C_1 (also Radium-C_2)
(Radon)
(a few days) (a few minutes) (less than ½ hour) (about 20 minutes) (infinitesimal time)

↓

Radium-D ⟶ Radium-E ⟶ Radium-F ⟶ Metallic lead
(about 20 years) (about a week) (several months)

It will be easily seen that with this sequence of changes, mostly rapid, the contents of our tube, originally containing pure radium, must gradually change to a strange mixture of new unstable elements. The disentangling of the separate processes in the sequence, and the discovery of the life periods of each, must surely be one of the greatest masterpieces of experimental skill in the history of Science; but what an anti-climax in the drama revealed! The alchemists of old tried in vain to bring about the transmutation of elements. They struggled to obtain gold from lead. And here we find Nature herself engaged in the work of transmutation, but in a direction opposite to that fondly hoped for by the alchemists. Lead! the common base and despised metal, as end product of Nature's alchemy, and from an element (radium) vastly more costly than our precious metal gold.

It seems like irony, yet it is true, and man's insignificance in the process is demonstrated by the fact that nothing he can do can, in the least, alter Nature's radioactive transformations. Neither heat nor any physical treatment at his disposal will alter either the speed or the nature of the processes spontaneously taking place. In fact, it can be shown mathematically that Man would need to have at his disposal temperatures of the order of 100,000 million degrees Centigrade, to produce quanta of the requisite high frequency to disturb the nucleus of radioactive or any other atoms.

Returning to the radium sequence of disintegrations, it is to be noted that some of these are accompanied by the

ejection of a helium nucleus (α-particle) as a by-product, just as when radium changes to niton. Whenever this occurs there is a loss in atomic weight of 4 and a drop in atomic number by 2, as already explained for the case of niton. This happens, for example, when the metal radium-F, which is Madame Curie's polonium, changes to common lead. But some of the changes do not involve the ejection of helium; instead, an electron is shot out of the nucleus with terrific speed (varying with different cases). This happens, for example, with radium-E, which incidentally is an isotope (see p. 256) of bismuth, when it changes to radium-F (polonium). Here there is no change of mass (for the mass of an electron lost is negligible by comparison), and so these two elements have the same atomic weight, though they are quite different in properties (such elements are called *isobares*); and it is necessary to explain why they are different. Now the nucleus of radium-E is composed of 210 protons and 127 "cementing" electrons and therefore has a net positive charge of 83 (210 - 127), thus requiring 83 orbital electrons to make the neutral atom. When this nucleus loses one electron, the newly formed nucleus contains still 210 protons, but of course only 126 "cementing" electrons. The net positive charge of the nucleus is therefore 84 (210 - 126), and as in the neutral atom this must be neutralised by 84 orbital electrons, it follows that the new atom (radium-F) has atomic number 84, whilst its parent (radium-E) had atomic number 83. The extra electron required for the new atom is provided by its surroundings, where mobile electrons in a free condition are always available. If not so provided the atom would not be neutralised; it would lack a valency-electron or be as we say "ionised" (see p. 254), forming what we call a positive ion. The essential point to bear in mind is that the newly formed element (radium-F) is absolutely different from its parent, and has totally different chemical properties, just as, say, bismuth (atomic number 83) is different from lead (atomic number 82).

In general, Rutherford's view of the structure of atomic nuclei is that they consist of two parts at least, (1) a tightly bound inner nucleus of protons and (2) an outside looser system of protons. Some of the protons are bound to individual elect-

rons, as so-called "neutrons" where each proton is somehow tied up with a single electron. It is the inner structure (1) which gives the minimum packing possible, and which predominates in the smaller atoms, whilst the outer system becomes more complex the heavier the atom.

A mental picture of what *might* be the case is given by the suggestion of Aston in 1920, that the inner nucleus (1) consists only of neutrons, whilst the outside portion (2) consists of unneutralised protons. If this is the case, the latter, which probably revolve round the inner nucleus, must be exactly equal in number to the total unbound electrons of the electronic rings, that is equal to the atomic number of the element. In any case, as we have seen, the total electrons of the entire neutral atom, including those in the nucleus, is exactly equal to the total number of protons—*i.e.*, the atomic mass.

But there is a great deal more yet to be found out about the constitution of atoms. A very curious thing, as yet unexplained, is the different nature of elements with even atomic number from those with odd. Even-numbered elements are usually more abundant on earth (oxygen, silicon, iron, etc.), and they may appear in several isotopic forms differing in atomic weights, which are both odd and even, by several units (mercury, for example, has 7 isotopes, varying between 196 and 204 in mass). Odd-numbered elements appear generally in only 2 isotopes (if any), whose atomic weights are generally odd and differ by only 2 units. These things are mysteries at present, which later research may clear up.

It is a very remarkable thing that, in the radioactive disintegration of atoms, it is always helium (as α-particle) which is ejected from the nucleus and never hydrogen (as proton). This strongly suggests that helium nuclei, ready-formed, as it were, are present in the complex nuclei of these heavy atoms.

In 1916, Sir E. Rutherford made use of α-particles to explore the nature of the atomic nuclei, and one of his most interesting experiments was carried out on nitrogen. If we imagine a large number of peas or any other small objects moving freely in the air and widely spaced, the chances of the most expert marksman, if even he could see his target,

hitting one of these peas with a rifle bullet would be exceedingly small; but if, instead, the gun were capable of discharging several hundred small shot at the invisible target, a collision between one of these pellets and a wandering pea might take place. Similarly, Rutherford exposed the wandering molecules of nitrogen gas to the bombardment of the infinitesimally small but incalculably numerous α-particles, with the result that some collisions between them and the nitrogen atoms in the molecules did take place. The terrific blow inflicted by the α-particle on the nitrogen atom resulted in the smashing of the latter and the production of two simpler bodies from it. One of these is a hydrogen atom, carrying a positive charge—*i.e.*, a proton or hydrogen atom that has lost its orbital electron, and the other is doubtful but appears to be an isotope of oxygen.

Now this is a very remarkable, indeed the first, example of transmutation of the elements by man. It is modern alchemy, but its theoretical significance is profound. For if oxygen is formed from nitrogen in this way, it must be an isotope of common oxygen (O=16) with an atomic weight of 17. Each new atom must have been derived from a nitrogen atom weighing 14, through a helium nucleus, weighing 4, actually penetrating the N-nucleus, staying there, and dislodging a proton weighing 1. Quite recently another isotope of oxygen, weighing 18, has been discovered in minute traces in ordinary oxygen, so that this element is no longer "pure," as it was supposed to be.

The deduction, from these and similar observations made on other elements, is that as already said the nucleus of an atom has a composite structure, containing hydrogen nuclei and probably also helium-like nuclei in some cases. Rutherford by his transmutation experiments has thus brought us back to Prout's hypothesis of over a century ago, and all the elements are in the long run multiples of hydrogen.

Applications of Electricity.—Although it is by no means the purpose of this book to describe the innumerable applications of modern physical theories and discoveries to matters of everyday life, a brief reference must be made to a very few of the inventions that are based directly on these discoveries

and that are familiar to everyone. Of these, perhaps, the most notable are the telegraph, the telephone and wireless telegraphy and telephony. We shall confine ourselves to principles; there are books in plenty in which details of the apparatus used in each case are given in full.

The Telegraph.—Starting with the conception of an atom as a positively charged nucleus surrounded by one or more orbital negative electrons, or units of negative electricity, the electric current may be conceived as a simultaneous passage or stream of electrons from atom to atom. The more freely the electron can so pass, the better conductor the material is. Magnetism is a force acting in the ether at right angles to this electronic stream, so that whenever a current passes along a wire an ethereal disturbance is set up round it which is termed a "magnetic field." What magnetism is in itself we do not know, and no satisfactory explanation has as yet been put

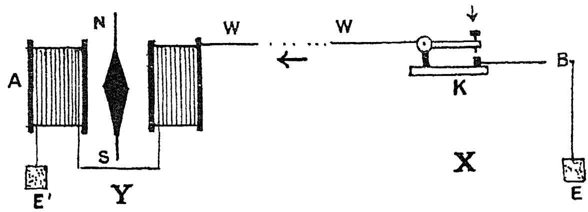


FIG. 97.—PRINCIPLE OF THE ELECTRIC TELEGRAPH.

forward of the relation that undoubtedly exists between electric currents and magnetic flux.

We have seen that, early in the nineteenth century, Oersted (p. 137) discovered that when an electric current flowed along a wire it had the power of deflecting a neighbouring magnetic needle to the right or the left, according to the direction in which the current was flowing. It is on this discovery that the electric telegraph is based, but it did not materialise until 1837, when Cook and Wheatstone, in Britain, and Morse, in America, invented the instrument that made long-distance communications possible. The general principle may be readily understood from Fig. 97.

The battery, B, is "earthed" on one side at E, and is in continuity with the key, K, on the other. When the key is depressed contact is made, and the current passes along the wire, W, to the coil, A, at the receiving station, Y, which in turn

causes the needle, NS, to be deflected. The circuit is completed by "earthing" the other end of the wire at E′. A tap on the key will cause a momentary jerk of the needle, while a more prolonged pressure will induce a longer deflection. If a code of "dot and dash" be agreed upon, indicating letters and figures, it is obvious that messages may be transmitted from X to Y. These messages are recorded by watching the movements of the needle, or by making the needle write its message on a strip of paper uncoiled from a revolving drum, and by other methods we need not describe. How messages may be sent on the same wire from Y to X ("duplex" and "quadruplex" systems), and for a description of the "siphon recorder," invented by Lord Kelvin for use in submarine telegraphy, books on the subject of telegraphy must be consulted.

The Telephone.—The telegraph transmits signs only; the next problem was how to transmit sounds, and the instrument used for that purpose is the telephone.

Sound travels through air at about 1,100 feet per second; it travels five times as rapidly through water, and fifteen times as fast through a steel wire—roughly, three miles per second—so that a sound produced at one end of a wire in London would be heard in Glasgow, 400 miles distant, about two minutes later—provided there be no dissipation of sound on the way due to molecular vibration of the wire. But such dissipation cannot be prevented; hence a simple wire connection between any two stations is quite useless unless the distance between them is very short. The principle of the modern telephone was discovered when, in 1876, Graham Bell found a method of transmitting sounds by electrical means.

In Fig. 98, D is a thin iron diaphragm which vibrates near a listener's ear. Behind the diaphragm is placed a magnet, M, and a coil, C. The to and fro movements of the diaphragm induce currents of varying intensity in the coil by electro-magnetic induction which pass along the wire, W, to the

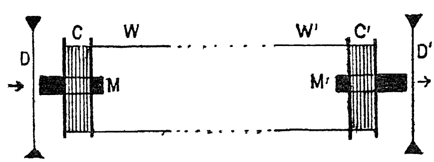


FIG. 98.—BELL'S TELEPHONE.

receiver, which acts in the reverse order, but is similarly constructed. The current causes the magnetic attraction to vary and, consequently, the pull on the diaphragm, D′, the vibrations of which reproduce the same air waves created by the voice at the other end. In the modern telephone the receiver is still constructed on the Bell pattern, but the transmitter now used is what is called a carbon microphone. The flaw in the Bell transmitter lies in the fact that the currents produced are of very low intensity, and consequently the receiver emits very feeble sounds. In the carbon microphone a film of mica receives the air vibrations caused by the voice; this film is connected with a carbon disc separated from a second, corrugated, carbon disc by a layer of carbon granules. The vibrations of the mica plate are transmitted to the first carbon disc, which induces variations in the state of compression of the carbon granules between it and the second disc. These changes in the compression of the granules are accompanied by alterations in their electrical resistance, which cause variations in the value of the current sent to the receiver at the other end of the line, and hence give rise to vibrations of the disc of the receiver.

Hertzian Waves.—We have already seen that the ear, and, behind it, the brain is able to receive and analyse the vibrations in the air, which we call sound, but that the capacity of the ear and brain in this respect is limited and determined by the frequency of the waves and the sensitiveness of the aural apparatus. Similarly the eye—and again the brain behind it—is adapted to receive and analyse those vibrations of the ether which we call light, but the capacity of the retina as a receiving apparatus is also very limited. A glance at the scheme on p. 107 shows how small a portion of the range of ethereal vibration represents the visible spectrum. It is only that part which includes wave-lengths between 0·000,078 and 0·000,038 cm. that affects the eye, and it is obvious that if the source of light be several miles away, even these waves may never reach the eye at all, unless, as in a lighthouse, the lamp be greatly elevated and various optical appliances be used to intensify the light. But there remains the entire range of waves beyond

the visible spectrum, beyond both the violet and the red ends. That such waves exist we have already seen abundant evidence.

In 1863, Clerk Maxwell put forward his famous electro-magnetic theory, in which he showed, theoretically, that any changes in electrical conduction created disturbances in the ether which were propagated outwards into space with the velocity of light. In 1887, Hertz, a pupil of the celebrated Helmholtz, and Professor in Carlsruhe, succeeded in demonstrating the existence of these waves in a very simple way. He used an apparatus called an "oscillator" (Fig. 99), consisting of an "exciter," A, and a resonator, B. The latter is merely a wire bent in the form of an incomplete circle, the free ends tipped with metal balls, half an inch apart. The exciter consists of an induction coil, C, the terminals being connected with two wires, ball-tipped and soldered to two plates, *d*, *d*. When the current is turned on a spark jumps across the gap in the resonator, which is placed some distance away. Hertz showed that the waves that passed from the exciter to the resonator travelled at the speed of light, and had all the characters possessed of light, save visibility. These waves are called "Hertzian waves," after their discoverer.

The chief difficulty was to find a sufficiently sensitive method of detecting the waves, but this problem was solved in 1890 by Professor Edouard Branly, of Paris. He discovered that when an electric spark was produced the electro-magnetic disturbance, so set up, had the power of altering the conductivity

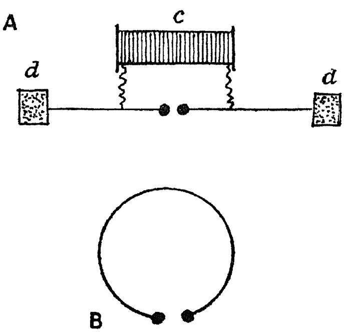


FIG. 99.—HERTZ'S APPARATUS.

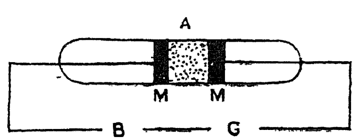


FIG. 100.—BRANLY'S COHERER.

of iron filings some distance away. Branly's apparatus consisted of a glass tube (Fig. 100) closed at both ends and containing two metal plugs, M M, to each of which a wire was

attached, the circuit being completed by a battery, B, and a galvanometer, G. Between the plugs, fine iron filings were loosely packed, A. Branly found that the resistance offered to the passage of the current by the metal particles was very greatly reduced when an electric spark from an induction coil was produced in the vicinity. In 1894 Lodge gave the name of "coherer" to this device, since the particles were conceived as cohering to each other when under the influence of the electric waves. The effect may be demonstrated very clearly by substituting an electric bell for the galvanometer, the bell ringing only when the electro-magnetic waves impinge on the coherer. When the hammer of the bell on its recoil is made to tap the tube, the coherence of the particles is broken and the current stops, but the particles are now in the condition to receive another impulse from the Hertzian waves. Numerous types of coherer have been invented since these early days of "wireless telegraphy." One of them was that used in the Italian navy, in which the metal filings were replaced by a globule of mercury placed between carbon plugs. When the waves impinged on the tube the mercury cohered to the plugs and completed the circuit, the coherence being broken when the waves ceased.

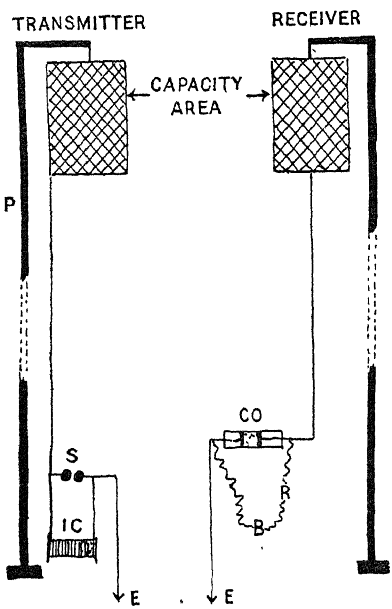


FIG. 101.—MARCONI'S FIRST APPARATUS.

Wireless Telegraphy.—Soon after Hertz's premature death, in 1894, a young student of physics in the University of Bologna, named Guglielmo Marconi, began experimenting on Hertzian waves. He greatly improved Branly s coherer, and, having obtained an introduction to Sir William Preece, the chief

engineer of the London Post Office, he induced him to take an interest in his inventions, and to experiment on them on a large scale. Marconi's first apparatus was built somewhat on the principle illustrated in Fig. 101. The transmitter consisted of a powerful induction coil, IC, its wires ending in large knobs only $\frac{1}{25}$ inch apart, S. The wave-lengths were one or two metres, and their frequency something like 250 million per second. The aerial was a sheet of wire netting called the "capacity area," hung from a lofty pole, P, connected with one knob of the exciter by an insulated wire, the other knob being earthed, E. The receiver was constructed on the same principle, only that the coherer, CO, took the place of the induction coil, and a battery, B, and a recorder, R, were introduced into the circuit.

In 1899 it was found possible to send wireless messages to France, and, after many more or less successful experiments, in December, 1902, a readable message was flashed between Glace Bay in Nova Scotia and Poldhu in Cornwall. Three years later Marconi hit on the idea of introducing horizontal "antennæ" or feelers, in place of vertical wire nettings, and this is the form so familiar to us nowadays on land and on ships. Since 1905 progress has been rapid and continuous, and now it is possible to transmit instantaneous messages from Britain to Australia, a distance of 12,000 miles. As in the case of telegraphy and telephony by wires, so in wireless transmission we can touch only on the general principle, and must leave all details to be studied in special treatises on the subject.

Relativity.

About fifty years ago there was born, at Ulm, in Württemberg, a boy called Albert Einstein, who became an official in the Patent Office at Berne. After publishing various papers on scientific subjects he was appointed professor of physics at Zürich, at Prague and, finally, at Berlin, where he succeeded the distinguished chemist van't Hoff. He had meanwhile become widely known as the originator of a new way of

regarding the universe, expressed in what is commonly called the "Theory of Relativity."

In such a book as the present it is quite impossible to give a succinct account of Einstein's Theory, and it is safe to say that no one except an expert mathematician can understand it, or could give a picture of it that would be intelligible to anyone unfamiliar with mathematical analysis. Einstein himself, when lecturing on the subject a few years ago, said: "I can tell you in one sentence what it is about. It concerns the connection or relation between electricity and gravitation. It is a purely mathematical theory, and therefore inexplicable to a layman." As this book is written for what Einstein calls "laymen," it would seem, at first sight, better to ignore the subject altogether, but to do so would be to omit what physicists, mathematicians and astronomers agree in regarding as one of the most fundamental conceptions, that science has to show in its development, since Newton.

When Huygens brought forward his undulatory theory of light he felt himself compelled to assume that all space was filled with an invisible, intangible something which he called "ether." No one has ever been able to demonstrate its existence, and yet without assuming that it actually does exist, many phenomena could not be explained. Clerk Maxwell showed that just as ether was necessary for the transmission of light waves, so it was required for the conveyance of other electro-magnetic waves which all travel at the same speed as light. Maxwell naturally concluded that light was electro-magnetic, and that the sensation of light was a cerebral interpretation of the beating of ethereal waves of a certain length on the retinal terminations of the optic nerve.

Now if ether fills all space and the earth is rushing through it at the rate of 66,000 miles an hour in its journey round the sun, it ought to be possible to detect some drift of the ether past it. In order to test this two American physicists, in 1882, carried out an experiment now known by their names—the "Michelson-Morley Experiment." They had at their command a method of measurement which enabled them to detect $\frac{1}{1000}$ inch in sixty miles, but into that method we need not go.

A simple analogy will show us the principle on which they worked.

If a river is four miles broad, and if an oarsman rows at the rate of four miles per hour, it is obvious that he could cross the river and return to his starting-point in two hours. If, however, he rows up the river for four miles while the stream has a velocity against him of two miles per hour, it is clear that he will require two hours to reach his destination. On his return journey he has this two-mile current to aid him, so that, with his own speed of four miles per hour, he can accomplish his task in forty minutes. His time, therefore, to travel up the river four miles and down four miles will be two hours forty minutes.

Michelson and Morley arranged a mirror, A (Fig. 102), parallel with the line of the earth's motion, and another at right angles to it, B, both at the same distance from a source of light, L. The times taken by a ray of light in travelling from L to A and back and from L to B and back were compared. After repeated observations no difference between the two periods could be detected, although the time of the journey to and from B might have been expected to be very slightly greater, if there were any drift in the ether, for the same reason that the boatman took forty minutes more in one direction than the other. The obvious deduction from these experiments was, either that there was no drift in the ether, or that the earth carried the ether with it.

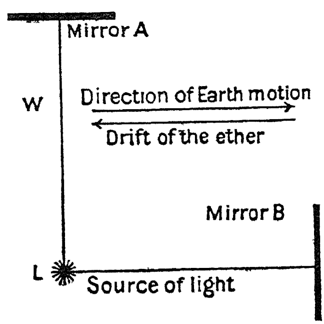


FIG. 102.—MICHELSON-MORLEY EXPERIMENT.

Although the problem was afterwards discussed for many years by leading scientists, no advance was made towards its solution until Fitzgerald, professor of physics in Trinity College, Dublin, put forward a startling suggestion which has led to some remarkable results. This suggestion was that the measuring instrument itself was also being shortened in the direction of

the movement through the ether, by such an amount as enabled Nature, so to speak, to cheat the observers of the results for which they were in quest. Fitzgerald evolved a mathematical expression involving the ratio of the velocity through the ether to the velocity of light, which gave the contraction necessary to account for the negative results obtained by Michelson and Morley.

The next step was taken by Lorentz, professor of physics in Leyden, who had been working at the same problem, and had carried out a considerable amount of mathematical investigation on the subject. Similar researches were also made by Larmor, an English mathematician, and it was really on the foundations laid by these men that Einstein began to build. He took a fresh view of the whole problem and published in 1905 a remarkable paper which presented an entirely new interpretation of the subject.

Perhaps the simplest method of explaining what the matter is all about, will be to give a summary of a few of the results that follow from the theory. To fix our ideas, let us suppose that there are two persons, A standing on a fixed platform, and B on a platform which can be run on a smooth straight track at any velocity. Each person is provided with various pieces of precisely similar apparatus—viz., a 12-inch steel rule, a clock with a pendulum, and a cube of iron or any other material. Suppose B's platform be moving at a steady velocity; but it must be remembered that the phenomena about to be explained become of sensible magnitude only when the velocity of B's platform is comparable with the velocity of light—viz., 186,000 miles per second.

1. Assume that the 12-inch steel rules possessed by A and B are lying parallel to the line of motion of B's platform. To A, B's rule will appear shorter than 12 inches, and to B, A's rule will appear to have shortened by the same amount. On the other hand, A's rule will appear unchanged to A, and B's rule unchanged to B. In other words, each observer thinks that the distance between any two points on the other's platform is less than it appears to the observer on his own platform. The observations of each observer are reciprocal—*i.e.*, the

observations of A with regard to B's apparatus are the same as those of B in reference to A's apparatus. It was Einstein who first pointed out this reciprocal nature of the observations, and showed that it was unnecessary to regard one platform as stationary. He further asserted that a fixed platform was an impossible conception, because there can be no absolutely fixed point in space, and that the only thing that has reality is the relative movement between the two platforms. Previous investigators, including Lorentz and Larmor, had treated the subject on the assumption of one platform being fixed, and had not envisaged the reciprocal nature of the observations.

In order that we may obtain a more precise idea of the contraction of the 12-inch rule, let us suppose that the velocity of B relative to A is represented by v, and that the velocity of light is represented by c. Let l be the length of the rule as seen by B, then the length, l', of the rule as seen by A will be equal to $l \times \sqrt{1-\left(\frac{v}{c}\right)^2}$. For example, suppose v is equal to half c, then the length l', as seen by A, will be $l \times \sqrt{1-(\frac{1}{2})^2}$ or $0{\cdot}87\, l$. The 12-inch rule would, therefore, appear to A to be 10·44 inches long.

Since c equals 186,000 miles per second, the value of v in the above illustration is obviously enormously greater than any velocity used in mechanisms of human construction. At the ordinary velocities to which we are accustomed, the contraction would be immeasurably small, and that is the reason why the phenomenon has never revealed itself to common observation. Further, we can see from the expression that as the value of v increases nearer and nearer to the value of c, the value of the fraction $\frac{v}{c}$ approaches nearer and nearer to unity, and consequently the value of the expression $\sqrt{1-\left(\frac{v}{c}\right)^2}$ approaches zero until, when v equals c, $\sqrt{1-\left(\frac{v}{c}\right)^2}=0$. If the platform is travelling at the velocity of light, the 12-inch rule, the platform and everything on it would appear to have on

length at all in the direction in which it is moving. If values greater than c be inserted into the expression, the value of $\sqrt{1-\left(\frac{v}{c}\right)^2}$ becomes imaginary, for we should be trying to find the square root of a negative quantity; so that we are compelled to admit that velocities greater than that of light are impossible.

2. Let us now consider the behaviour of the two clocks, which are assumed to be identical in every way, so that, if placed side by side on the same platform, the pendulums would beat at precisely the same rate. But when A observes B's clock on the moving platform, he finds that the pendulum makes fewer beats per minute than his own clock does, and, reciprocally, B observes the same fact with regard to A's clock; each observer sees no change in his own clock, but *thinks* that the other clock is beating more slowly than his own. This part of the theory is a mathematical consequence of the phenomenon described in Section 1.

Expressed mathematically, if t represents the time between two beats of A's clock, then t'—*i.e.*, the time between two beats of B's clock—according to A's observations, is $\frac{t}{a}$ where a stands for the expression $\sqrt{1-\left(\frac{v}{c}\right)^2}$. Suppose, as in the previous case, B is travelling at a velocity, v, which is equal to $\frac{1}{2}c$, and that A's clock makes sixty beats per minute, then A would imagine that B's clock makes $60 \times \cdot 87$ or $52 \cdot 2$ beats per minute. If the velocity of B's platform increases, the pendulum of his clock will appear to A to beat more and more slowly, until, when the velocity of the platform equals that of light, the pendulum will appear to A to be stationary.

One point must be carefully noted—viz., that the dimensions of bodies measured at right angles to the direction of the relative motion are quite unaffected by that relative motion.

3. Consider next the case of the two similar iron cubes. When there is relative motion between the two platforms, A will think that the mass of B's cube is greater than that of his

own cube, and, conversely, B will think that A's cube has a greater mass than his, though each observer will notice no change in his own cube. Thus, suppose A were able to act on B's cube by means of a suitably applied force, operating at right angles to the lines of motion, A would find that a greater force would be required to produce a certain acceleration, in the line of the applied force, than would suffice to produce the same acceleration in his own cube, and, reciprocally, for B.

If m represents the mass of A's cube, then the mass of B's cube, or, to be more precise, the "transverse" mass, will appear to A to be $\frac{m}{a}$. Thus if A's cube weighs 10 pounds (masses being compared by comparing their weights), and if, as before, B is travelling at half the velocity of light, then, according to A's reckoning, B's cube, when an attempt is made to cause a deviation in it at right angles to its line of motion, has a mass equivalent to $11\frac{1}{2}$ pounds. An actual example of this phenomenon is to be found in the passage of electrons from the cathode to the anode in a discharge tube. As the voltage between the cathode and the anode is raised, the velocity of the electrons increases, and the mass also increases according to the above mathematical expression, as can be demonstrated by causing the electrons to deviate from the straight path by external electrostatic and magnetic fields. This experiment was carried out by Sir J. J. Thomson years before Einstein put forward his theory, and he obtained a mathematical expression representing the increase of mass, but was unable to give any reason for it.

4. As the result of further research Einstein obtained an expression which gives the total energy of a body in motion, which consists, first, of the energy, a, within the body itself, existing apart from the motion, and, second, of the energy, b, due to its motion relative to the observer. What we call the "mass" of a body is attributable to this internal energy, a. "Mass" is the manifestation to us of this internal energy, and thus the terms "mass" and "energy" are interchangeable. The component, b, is simply the ordinary kinetic energy of a

moving body ($\frac{1}{2} mv^2$), familiar in general treatises on dynamics. The atomic energy contained in 1 pound of any material—*i.e.*, in a mass of 1 pound—would be capable, were it possible to release it and use it in a suitable manner, of raising 25,000,000 tons to a height of 100 miles!

This conception is far-reaching. For instance, if 56 pounds of quicklime are combined with 18 pounds of water, the result is, so far as all experience shows, 74 lbs. of slaked lime (p. 167), plus the heat produced during the combining of these two substances, and lost. Now, since heat is a form of energy, and since energy is equivalent to mass, the dissipation of heat represents a certain loss of mass and therefore of weight, and, in consequence, the amount of slaked lime produced must be less than 74 pounds in weight; but the difference is so infinitesimally small as to be entirely beyond the ability of the most delicate balance to detect. The heat given out by the sun must likewise represent a loss of mass by the sun, and that is the view held by modern physicists, and it doubtless accounts largely for its immense heat resources (see p. 309). The same thing also applies to the stars.

5. Suppose that B has a small trolley on his own platform, carried on a track on this platform, lying parallel with the track on which his own platform runs, and suppose that this trolley is running on its track in the same direction as that in which the platform is running, what velocity will the trolley appear to have relative to B and relative to A? If the velocity of the trolley be v_1 relative to some point on its own track, then this is the velocity which B would ascribe to it. Let the velocity of B's platform relative to A be v_2, then it would be natural to suppose that the velocity of the trolley relative to A would be v_1+v_2. Taking ordinary velocities, let v_1 be ten miles per hour and v_2 be twenty miles per hour, then from A's standpoint the velocity of the trolley is $10+20=30$ miles per hour. But, according to the theory of relativity, this is not the case; and just as length, time and mass are insensibly affected at ordinary terrestrial velocities, so they are in the above example for the number chosen. If, however, the velocities v_1 and v_2 are of enormous magnitude—*i.e.*, comparable with

the velocity of light—the velocity of the trolley, according to A, would be less than v_1+v_2, and would be:

$$v_3=\frac{v_1+v_2}{1+\frac{v_1\times v_2}{c^2}}.$$

Let $v_1=\frac{1}{2}c$ and $v_2=\frac{1}{4}c$, then $v_3=\frac{2}{3}c$ or 0·66c. If the velocities were simply added, as in the first example given, the velocity of the trolley relative to A would be 0·75c. According, therefore, to the theory of relativity the velocity of the trolley, relative to A, is less than that given by the ordinary method of combining velocities.

In 1851 Fizeau, an eminent French physicist, carried out an experiment in which two rays of light were passed through moving columns of water contained in long glass tubes. The velocity of the flow of the water was the same in each tube, but the direction of the flow in one tube was the same as the direction of the light ray, and in opposition to it in the other. It might naturally be expected that the velocity of the light in the first tube would be increased by that of the water, and decreased in the second by the same amount. But actually it was found that the effect of the velocity of the water was entirely different, and although a mathematical equation was formulated which agreed with the tests, and which is, incidentally, derivable from that given above for the compounding of velocities, the explanation remained a complete mystery until Einstein found the solution, wherein he used the new method of combining velocities.

It is interesting to study the effect of substituting various values in the equation given above. Suppose, for example, that B directs a ray of light from a lamp on his platform in the direction of movement of his platform, what will the velocity of this light appear to be to A? Substituting c for v_1 in the equation, we obtain

$$v_3=\frac{c+v_2}{1+\frac{c\times v_2}{c^2}}=\frac{c+v_2}{1+\frac{v_2}{c}}=\frac{c+v_2}{\frac{c+v_2}{c}}=\frac{c+v_2}{c+v_2}\times c=c$$

—that is to say, the velocity of the light as viewed by A is unaffected by the velocity of B's platform.

Let us next imagine that B's platform is travelling with the velocity of light, what will now be the velocity of the ray of light projected from B's platform, so far as A is concerned? This means that both v_1 and v_2 have now the value of c in the equation, and on substitution we obtain

$$v_3 = \frac{c+c}{1+\frac{c \times c}{c^2}} = \frac{2c}{1+1} = \frac{2c}{2} = c,$$

so that we arrive at the velocity of light once more.

From this we conclude that the velocity of light (*in vacuo*) is constant and the same for all observers, whether they regard themselves as stationary or in motion. Surprising as this result may seem at first, it is only what one would deduce from the final interpretation of the Michelson-Morley experiment—viz., that the velocity of light *in vacuo* is a constant.

6. In Section 1 we tried to explain how relative motion affected the apparent length of a body, or, in other words, the apparent distance between any two points in the line of motion, and in Section 2 the apparent period of time between two occurrences. Suppose that two observers in motion relative to each other observe the same phenomenon, say, on a distant planet, how will the phenomenon appear to each observer? Suppose that A regards himself as stationary, and that it is B who is in motion, then the distances measured on the planet will appear greater to A than to B, whereas intervals of time between occurrences will appear less to A than to B. When the observers meet and compare notes their records of the same phenomena will not agree. Can their readings be reconciled? They can, but only by using mathematical expressions and conceptions which combine both distance and time, or, as properly expressed, space and time. This combination gives rise to the conception of a space-time continuum—*i.e.*, an all-pervading extension analogous to ordinary space, but having four dimensions, three in space and one in time.

It is quite impossible to form a mental picture of a space-time

continuum; it is purely a *mathematical* entity. In the space-time continuum occurrences are called "events," and the separations between them "intervals." In the case suggested above, the two observers would now find that the intervals between successive events, as witnessed by them separately, would agree; and if expressed mathematically in terms of space and time, all natural laws would be the same *for all observers*, no matter whether they were on the same or on different platforms, moving relatively to each other, a condition of affairs that cannot be realised by using the expressions of classical dynamics (Newtonian space and time).

In all the results we have given above of the effect of relative velocity on the observations of A and B, it was assumed that the relative velocity remained the same during the period of the observations. This part belongs to what Einstein calls the "Restricted or Special Theory of Relativity." Only a few of the implications of this part have been mentioned, but these, it is hoped, may have given a general idea of the nature of the subject.

Einstein next tackled the much more difficult problems coming within the scope of the "General Theory." The General Theory, which includes the Restricted Theory, was published in 1915, and deals with problems in which there is not a constant relative velocity, but, instead, a constant relative acceleration—that is, a constant change in velocity between the observers, and on this work he based his famous theory of gravitation.

Gravitation appears to us as a force of attraction between the earth and all bodies on its surface. (We need not concern ourselves here with the attraction between the heavenly bodies.) Newton regarded gravitation as a force, and his dynamics are based on the assumption of a force of attraction existing between all bodies; but the seat of the force, how it is produced and how it acts on these bodies, have always been profound mysteries.

As we explained before, there are forces existing between electrically charged bodies, such as pithball and a rubbed glass rod, which resemble gravitational force, but with

at least one great difference—viz., they not only attract but may also repel. Forces of attraction and repulsion also exist between magnets, and in the case of pieces of iron, nickel or cobalt in a magnetic field. But, unlike electric or magnetic forces, gravity always attracts and never repels. It acts on all bodies, no matter of what substance they are made, and gives to all of them, when free to fall, exactly the same acceleration. These characteristics are of remarkable significance, as we shall see later on; meanwhile, let us make a few hypothetical experiments in order to clarify our ideas.

Suppose we have a trolley running on a straight, level track, and that when in motion there is no frictional resistance due to the axle bearings of the trolley on the track, and no resistance from the air. (Of course, in making these suppositions, we lay ourselves open to the criticism that the wheels and the axles of the trolley ought to be assumed to be massless, but we may offer the excuse that we are not writing for experts.) Now we know from everyday experience that the trolley will not start from rest unless we give it a push or a pull—in other words, unless we apply force. It is also common experience that it requires a greater force to set a heavy trolley in motion than a light one. What is the precise effect of applying different amounts of force to the trolley—the line of the force being, of course, that of the track? The trolley contains a certain quantity of matter or material; we think of this as "mass," and the force of gravity acting on this mass gives it what we call "weight." In everyday life masses are compared by estimating their weights, although this is not the only possible way of comparing them.

Let the weight of the trolley be 322 pounds (this number is selected simply because it renders the arithmetic easy). If we apply a force, either a push or a pull, of 10 pounds (the force being equal to that of this weight) along the track, the trolley will start from rest, and, as long as the same force is continuously applied, the velocity of the trolley along the track will steadily increase at the rate of 1 foot per second in each second. The force is 10 pounds, and the acceleration is unity; the ratio between them, therefore, is 10 to 1.

If we alter the value of the force this ratio will still hold good, and, hence, we should find that with a force of 322 pounds —*i.e.*, a force equal to the weight of the trolley—the acceleration would be 32·2 feet per second in every second.

But this acceleration is what is found by experience to be the case when a body falls by the force of gravity (strictly speaking, at London). So we see that when the applied force is equal to the weight of the body, the acceleration is the same as that which would be produced were the body allowed to fall in the earth's gravitational field; in other words, we have produced artificially what would be done by the natural attraction of gravity of the earth.

Obviously if we double the mass of the trolley we must apply twice the force to obtain the same acceleration, and that is precisely true of weight in the earth's gravitational field. It is not of the slightest consequence of what material the trolley is made; all that matters is the mass, and again this agrees with our experience of the force of gravity.

It is important to note that, in the experiments with the trolley, the force of gravity acts perpendicularly to the line of the applied force and of the motion, and therefore it could have had no effect on the results, which would have been the same had the experiments been carried out in interstellar space, where a gravitational field may be neglected. The trolley would have no "weight" in interstellar space, although it would still have the same mass as before.

It is this "mass" that gives to all bodies their property of "inertia"—*i.e.*, their unwillingness to move, if at rest, unless compelled to do so by the application of a force, and also their unwillingness to stop, if in motion, unless a counterforce be applied, which will produce a "deceleration" or decrease in velocity of so many feet per second in every second. The counterforce must cease the instant the body comes to rest, otherwise it would immediately afterwards begin to accelerate the body in the reverse direction. (Note that the terms "in motion" and "at rest" are to be taken as relative to the observer.)

Most of us remember Jules Verne's story "From the Earth

to the Moon," and how the hero of the tale is shot out of a gigantic cannon, pointed vertically, in a projectile as large as a small room. Let us imagine ourselves in such an immense shell, but that instead of being shot upwards at a prodigious velocity, the projectile has an upward acceleration of 32·2 feet per second in every second, gravitation in the reverse way, so to speak. At the same time let us assume that the force of gravity of the earth does not exist. Inside the projectile we should experience a force of exactly the same nature as we do in the earth's gravitational field.

For example, a body resting on a table in the projectile would be urged upwards, along with every other thing in the projectile, with an acceleration of 32·2 feet per second, and would press on the table by the same amount as it would do on the earth's surface in its gravitational field. If pushed off the table the body would have no support to sustain the pressure it exerted on the table, therefore no applied force to urge it; it would lag behind the other moving bodies, and, to us in the projectile, would seem to fall to the floor with an acceleration of 32·2 feet per second in every second, exactly as a falling body does on the earth's surface. This, then, is the meaning of gravitation—it is the result of an acceleration. Professor Eddington tells us that "gravitational fields of force are illusions. The apparent force arises solely from acceleration, and there is nothing of gravitational force at all. A gravitational field of force at any point in space is in every way equivalent to an artificial field of force resulting from acceleration, so that no experiment can possibly distinguish between them."

Now, a gravitational field can not only be created, it can also be destroyed, for were the projectile to fall back to earth under the attraction of gravity—it being assumed that there was no air resistance and that the fall was absolutely free—we, in the projectile, should find that all evidence of a force of gravity had entirely disappeared. A body released from our hand would seem to float in space, because it would be falling towards the earth, along with the projectile, at exactly the same speed. A body pushed off the table by a force acting parallel to the floor would cross the projectile in what we,

inside the shell, would regard as a horizontal direction and hit the opposite wall at the same level as that of the table. To an observer stationed on the earth, however, and able to see through the wall of the projectile, the body would seem to describe a parabolic curve, just as a body thrown horizontally at the earth's surface would do.

Reverting to the rising projectile, it would appear that in order to produce the effects we observed therein on the surface of the earth, the earth would have to increase in size with a constant acceleration—that is to say, the radius would have to increase at the rate of 32·2 feet per second in every second. But we know, of course, that the earth is not behaving in this grotesque manner. What, then, is taking place? Einstein holds the view that the phenomenon of gravity, acting on a body, is not attributable to the attraction of the earth at all, nor to an increase in the length of the radius of the earth, but to the condition of the space-time continuum in the neighbourhood of the body. The idea is analogous to that put forward by Clerk Maxwell for electrically charged bodies. Maxwell considered that the seat of the phenomenon was outside, and not inside the body. For instance, he thought of the energy of an electric current that was being carried by a conductor, as residing in the field outside the conductor, which simply acted as a guide to the current.

Einstein developed a number of equations which describe the properties of the space-time continuum where a gravitational field does not exist—say, for example, in interstellar space—and also a number of equations which describe the properties of the space-time continuum in gravitational fields. In the case of the former the mathematical forms of the equations resemble those appertaining to geometrical figures drawn on a flat surface, where the continuum is, so to speak, "flat"; in the second case, the forms resemble the ordinary equation for figures drawn on curved surfaces—*i.e.*, a sphere—and the continuum in a gravitational field is "curved." This explains the statement circulated some years ago that Einstein had said that space was "curved." Einstein was referring to the space-time continuum and not to space in the ordinary sense of the term.

It is impossible to visualise either a flat or a curved continuum, and the terms "flat" and "curved" are, as we have already tried to explain, based simply on the analogy between space-time equations and those used in ordinary mechanics.

Einstein made three predictions by which he said his theory might be tested. They were as follows:

1. The perihelion of the orbit of Mercury moves round the sun in the course of centuries. The observed advance is 574 seconds per century, but Le Verrier (p. 87) calculated that, in accordance with Newtonian dynamics, the time should be 532 seconds; and since his day the solution of the discrepancy of forty-two seconds has baffled the ingenuity of all the mathematicians and astronomers. Working on his new theory, Einstein has repeated these calculations and showed complete agreement to exist between observation and calculation.

2. Light is a form of energy; it is of the same family as heat, and from what has been said (see pp. 268-270), it follows that light has mass. It, therefore, must be subject to gravitation. Keeping this fact before him and using his new theory of gravitation, Einstein predicted that a ray of light coming from a distant star and passing close to the sun's disc would be displaced by 1·75 seconds of arc. In order to test this, observations were made during the eclipse of the sun which took place on May 29, 1919, and as a result of this and later eclipses astronomers are satisfied that Einstein's prediction is fulfilled.

3. A spectral line should be displaced towards the red end of the spectrum by an amount, depending on the strength of the field of gravity through which the light passed. The strength of the gravitational field of the sun is immense, and to test the theory observations have been attempted on sunlight. The experiment is, however, one of extreme difficulty; and, so far, no definite results have been obtained one way or the other, doubtless because the sun's gravitational field, great as it is, is not sufficiently intense. Such intensity can only be found in the case of massive dwarf stars (p. 310), and it is interesting to note that recent confirmation of the spectral shift, predicted by Einstein, has been found in the case of the massive dwarf

companion of Sirius, the density of which is prodigious and whose gravitational field at the surface is therefore enormous.

The advent of Einstein's theory implies that many ideas of the older dynamics must be scrapped, but its refinements, which are necessary in modern physics and in certain astronomical work, are negligible in many applications of science. On the other hand, Relativity, by its implications, has rendered obsolete the old system of Philosophy based on Newton and Descartes, also many familiar conceptions, as we shall see (p. 338) when we come to consider astronomical space and time.

We have given considerable space to the discussion of this very difficult and abstruse subject, but some explanation seemed called for in view of the great interest aroused by Einstein's theory since it was first promulgated, and the importance ascribed to it at the present day by astronomers, physicists, philosophers, and mathematicians alike.

§ ii. Modern Astronomy

The great advances made in astronomy during the latter half of the nineteenth century were mainly due to the greater instrumental perfection of the telescope and spectroscope, aided by photography; and by these means an immense mass of information was accumulated concerning the distances and nature of stars and nebulæ. But it is only within the last thirty years, with the aid of newer instruments, such as the great 100-inch telescope at Mount Wilson and the interferometer of Michelson, used in the clear skies of America, that data have been obtained enabling astronomers and mathematicians to bring the universe into true perspective. We can, of course, only give a bare survey here, dealing with the nearest objects first.

The Moon.—The first object in the heavens that Galileo studied with his newly discovered telescope was our nearest celestial neighbour—the moon. Astronomers from his day, almost without exception, down to quite recent years have always regarded our satellite as a small dead world, without

any atmosphere, and showing no activity of any kind. There was no water on it, and hence there could be no denudation; the volcanoes were all extinct; and since there was no water and no air there could be no life. It was nothing but a rough stone swinging round the earth once a month and passively reflecting the sun's rays to us when it was in the proper position to do so. The only one of any importance who ventured to express the possibility of there being life on the moon was the great astronomer Sir William Herschel, but his views on the subject were only vague and hesitating.

In 1887 a great work on the moon was published by two German astronomers, Mädler and Beer, illustrated by a profusion of maps giving details of the mountain ranges, volcanoes and plains, and these authorities came to the conclusion that the lunar world was "changeless, airless and lifeless." But this view was not accepted by some observers, who thought they had detected alterations in the form of some of the volcanoes and in the great plain called "Plato" in the lunar maps. One of these was Professor Pickering of Harvard University, who, in 1900, established an observatory in Jamaica. He brought to his aid the art of photography, which had grown to be a valuable asset to the astronomers of the last decades of the nineteenth century. Pickering concluded that the moon was not a dead world, but that it had an atmosphere, though an extremely rarefied one, containing carbon dioxide and water vapour, and that some of its volcanoes were still feebly active, giving out clouds of dense gases. The white linings of some of the craters he believed were due to hoar frost, frozen water vapour that had never gone through the liquid condition, and he urged the possibility of the existence of vegetation of a very low type. We now know, however, that the moon is too light an object to retain any appreciable atmosphere (see p. 361); and without this, life as we know it is impossible.

The Sun.—One of the first obvious facts known about the sun was the existence of spots on it, by watching the movements of which it was discovered that it revolved on its own axis once in about twenty-five days. By the seventeenth century, also, the sun's distance from us was made out to be 87 million miles,

certainly several millions too little, but not a bad approximation. In the eighteenth century Sir William Herschel studied the spots more carefully, and concluded that they were gigantic holes through which the dark solid core was visible (p. 163). After Herschel's time, about the middle of the nineteenth century, a German apothecary, called Schwabe, after observations extending over more than forty years, established the fact that the number of sun spots passed through a cycle lasting for about eleven years, and interest in these spots increased when it was discovered, soon afterwards, that the rise and fall in their numbers were coincident with magnetic variations on the earth.

Another curious discovery made about the same time was that while the sun was rotating at the equator in twenty-five days, the region between the equator and the poles lagged behind as much as two and a half days, and considerably more nearer the poles; further, that the belt of spots moved gradually closer to the equator and then died out, while new belts appeared in higher latitudes.

By this time astronomers had distinguished next the solar body an envelope which was called the "photosphere," or light-giving layer, surmounted by a "chromosphere," or solar atmosphere proper, composed of less heavy gases, outside which again was a silvery haze or "corona," visible only at times of total eclipse. From the chromosphere shot out from time to time immense red flames (hydrogen), which reached a prodigious height.

After 1860, when Kirchhoff had provided us with that invaluable instrument, the spectroscope, Lockyer, it may be remembered (p. 164), discovered the new element helium, in the chromosphere, which was identified, in 1898, as a constituent of the earth by Ramsay. Another notable discovery, made by Doppler of Prague, also about the middle of the century, was that the lines of the spectrum were displaced towards the violet end when the source of light was approaching, and towards the red end when it was receding, and thus we were able to follow to some extent the movements of the so-called "fixed stars" in the heavens (see p. 323).

In 1891 a new instrument was brought into use in the investigation of the sun. This was the spectro-heliograph, the invention of G. E. Hale, the Director of the great observatory at Mount Wilson, California. Professor Sampson of Edinburgh, the Astronomer-Royal for Scotland, describes this apparatus in the following terms: "In the photograph of a spectrum each line is a record of the presence and the state of a separate chemical element at the spot on the disc to which the slit is directed. If this record could be read for that special line for the whole disc, we should have the same information summed up for the whole sun. Let the light from the line in question be allowed to pass to the photographic plate, by means of a second slit, at the focus of the camera, the jaws of which shut off all the rest of the spectrum. Let both the first and the second slits be long enough to extend right across the image of the sun. Move the image of the sun across the first slit, then the light which passes through the second slit will come at every moment from different strips of the sun's surface; and if the photographic plate be moved behind the second slit, in unison with the movement of the sun's image across the first slit, a record will be given, not of the radiations of every substance mixed together, as in ordinary photographic or visual observations of the sun's disc, but of the states of some isolated substances, such as hydrogen or calcium, and even of different strata of these."

With the aid of the magnificent equipment of the Mount Wilson Observatory, Hale was able to announce in 1908 "that the sunspots were caused by vortices in the solar atmosphere." In 1896 Zeeman of Amsterdam had shown that the lines of the spectrum are widened and even split into several lines when the light comes under the influence of a strong magnetic field. Hale applied this "Zeeman effect," as it was called, to the sunspots, and was able to show that the vortices were electrical, and in 1922 he went a step further by noting that the spots were associated in pairs of opposite magnetic polarity.

So much for the surface of the sun. What is it like inside, and how does it compare with other suns—*i.e.*, stars? The answer is to be found in the wonderful mathematical analysis

by men like Emden, Eddington, and above all by Sir James Jeans, as revealed in his recent books on the nature of the universe (*Cosmogony and Astronomy*, and *The Universe Around Us*). The story, so far as the sun is concerned, makes the latter to be a very average kind of star, born some 5 or 6 million million years ago along with other stars out of a gigantic nebula, the sun being then considerably larger and more massive (perhaps three or four times heavier) than it now is. During this long period of time it has been (and still is) wasting away, relatively quickly at first but more slowly now, by the annihilation of the matter of which it is composed (see p. 269), with emission of a corresponding amount of radiation energy.

There is no other imaginable source of energy which could last so long, and Jeans supposes that it is mainly elements of atomic number 95 that contribute to this annihilation—that is to say, elements which do not exist on the earth (uranium, of atomic number 92, being the highest). These hypothetical massive atoms will mainly be found in the central region, which is the principal store of energy, and on this account they do not appear in the surface spectrum or on the planets which were born out of the surface layers of the sun, as we shall see later (p. 332).

On Jeans' theory the sun is not to be regarded as a ball of glowing gas greatly compressed at the centre, as Emden and Eddington regard it, but rather as a "liquid" core, of density about 140 times that of water, surrounded by a gaseous envelope, the outer surface of which we see. But this liquid core has very different properties from any liquid we are acquainted with on earth. One of the densest liquids we know is mercury (less than fourteen times that of water), but in the material of some so-called "dwarf stars," like the small companion of Sirius, we have densities of 50,000 or even more. So here is something very strange.

What, then, is this liquid interior of the sun and stars, whose density may vary between say 140 and several hundred thousand? As the heaviest matter on earth (the element osmium) is only about twenty-two times as heavy as an equal bulk of water, and compression does not make much difference, there

is only one satisfactory answer to this question. The liquid matter must consist of atoms which have been more or less completely stripped of their outer shells of electrons (see pp. 246-252) and so can get closer together on compression. It is these outer shells which, as we have seen, give the average atom its extreme emptiness, and so endows ordinary matter on earth with its ordinary relatively light properties. As we have seen, practically the whole of the mass resides in the nuclei, but if the nuclei of contiguous atoms are kept at (relatively) vast distances apart by the whirling rings of electrons surrounding the nuclei, it will be apparent that the most striking thing about ordinary matter, as we know it, is its extreme emptiness. But if we imagine, under the high temperature influences obtaining in the stars, the successive shells to be stripped away, then the effect of excessive heat will be to enable the nuclei to get closer together, provided that the pressure is sufficient to compensate the increased kinetic energy; to get nearer together, at any rate, than they ever could get together, whatever the compression, as neutral atoms fully endowed with their electron rings.

Now Jeans' theory of electron-stripping is no wild dream; it is most abundantly confirmed by experimental and observational evidence, so far as a few of the outer ring electrons are concerned —that is to say, at comparatively low temperatures of a few thousand degrees. It is, then, extremely likely that at temperatures of millions of degrees, which certainly prevail in the interior of the sun and stars, this process would be carried further, and in some cases to the extreme limit of complete stripping of all the electron rings down to the bare nuclei. Then we would get the "dwarf" stars (see p. 327), where matter is so dense that a single drop of the liquid might weigh 10 lbs. Take, for example, the atom of uranium, which contains 238 protons in a nucleus surrounded by 7 successive electron rings, K-, L-, M-, N-, O-, P-, and Q- (see p. 251). The Q-ring containing only 1 electron is easily shed in the cold, and as the temperature rises the 13 electrons of the P-ring are shed, followed by the O-ring and so on till we come to the K-ring, the last stronghold of 2 electrons, which requires an enormously high temperature

to be shifted. It is very significant that the stars generally fall into groups, which can be identified as having shed successive rings down to a given one of the above, but with no stars in between. This shows that as each successive ring is stripped off, with the rising temperature caused by the annihilation of matter, there is a more or less sudden contraction in the size of the star to suit the smaller space occupied by the atoms newly stripped. The atoms of the giant red stars (see p. 319), like Betelgeuze, are stripped down to their M-rings; others which are smaller and yellow are stripped down to their L-rings; but the great majority of stars, known as the Main Sequence stars, are stripped down to the K-rings, whilst in the massive dwarf stars the atoms are mainly present as bare nuclei. Since in these dwarfs the electrons cannot reach the nuclei, the latter are protected from annihilation, though extremely hot; for annihilation involves the mutual disappearance of a proton and electron into a violent splash of radiant energy (see p. 269). Our sun belongs to the Main Sequence, but its constitution is such that it seems to be disconcertingly near the point at which the last (K-) ring is stripped off, prior to transition to a dwarf. When this happens it will shrink in size to a quite tiny object as seen from the earth, and as it will then emit only $\frac{1}{400}$ of its present radiation, the sun would no longer be any use to us—all life on earth would cease, the oceans would freeze and the air liquefy. But although the sun is in this dangerous condition, there is no need for us to worry; so great are time magnitudes in the scale of the universe that Jeans calculates that the sun might easily go on as it is for another 2 million million years, in spite of the fact that in terms of astronomical measurements it is near the verge of changing over.

The liquid core of the sun, consisting for the most part of heavy atoms, exceeding uranium in atomic number and carrying only the single K-ring, is not spherical but ellipsoidal, owing to its relatively rapid rotation compared to that of the visible surface. It is the disturbance caused by the protuberant ends of this ellipsoid which agitates the gaseous envelope, producing the whirlpool storms which we call sun-spots, and makes the surface layers rotate more rapidly in the equatorial regions than

in higher latitudes. The 11-year periodic variation in the number and position of the sun-spots may be due to the influence of Jupiter, whose period of revolution is about 12 years, but this is very doubtful.

Our sun, as we have said, is only a very ordinary kind of star with nothing sensational about it. It is simply one of the myriad stars forming a compact but stupendous block known as the Galaxy (p. 324), which is visible on any clear moonless night as the belt, called the Milky Way, encircling the heavens. This block, or rather cake, because it is shaped something like a thick biscuit, is quite a small piece of the universe; but nevertheless all the stars we see are contained in it, while their brightness depends partly on how big they are and partly on how far they are off (see p. 329).

The Planets.—After the discovery of Neptune, in 1846, the sun's family circle consisted of eight planets, four smaller, inner ones—viz., Mercury, Venus, Earth and Mars—and four very much larger, outer ones—viz., Jupiter, Saturn, Uranus and Neptune. Between the orbits of Mars and Jupiter there was an immense gap of over 340 millions of miles, filled with a zone of over a thousand asteroids, the smaller members of which are still being discovered, and one of which (Eros) in its elliptical orbit round the sun sometimes approaches close to the earth. The origin of the asteroids is dealt with on p. 337.

During the past fifty years much research has been carried out on the planets, for most of which we have to thank the Italian astronomer, Schiaparelli.

Mercury.—Schiaparelli, in 1882, stated that Mercury, which revolved round the sun in eighty-eight days, had an axial rotation of the same period, so that it always presented the same face to the sun; one side of the planet was thus in perpetual light and the other in perpetual darkness. The American astronomer, Lowell, in 1897, affirmed that Mercury had no atmosphere, no water and no life—"the bleached bones of a world," he called it, and this view is now generally accepted. The temperature of the side of the planet facing the sun must be about 350° C.—*i.e.*, more than enough to melt

lead; on the other side it must be freezing cold, because there is no atmosphere to transmit heat by circulation.

Venus.—Schiaparelli also studied Venus, and believed that, as in the case of Mercury, one side was always illuminated while the other was always in darkness, for the periods of revolution and rotation seemed to be the same—viz., 225 days. Other observers, however, have stated that there is quick rotation, and the temperature observations, which show small differences between the illuminated and dark portions of the disc, confirm this view. The difficulty is that, owing to its cloud-capped atmosphere and the rare appearance of any markings, rotation is not apparent, but the conflicting statements would be reconciled by the hypothesis of Pickering (1921) that the period is about three days, with the axis of rotation almost lying in the plane of the ecliptic, and not approximately vertical as with other planets. The planet has a dense cloudy atmosphere, although the presence of water vapour is regarded as doubtful. The temperature of Venus, according to the Mount Wilson authorities, is just about freezing-point, which is somewhat remarkable seeing that Venus is so much nearer the sun than Mars, where the temperature is much higher. As the temperature observed, however, is no doubt that of an upper atmosphere, whereas that of Mars is a solid-surface temperature, the discrepancy is intelligible. In the case of the earth the upper air is colder than the surface air, as we shall see later (p. 369). The temperature in fact falls with increase of height for the first few miles (the so-called troposphere) and then remains more or less steady in the layers above (the stratosphere). The temperature of the stratosphere may be 60° C. lower than that at the surface, though at 40 miles it is actually higher.

Mars.—Mars is the next planet beyond the earth, and has always been an object of special interest. Again, it is to Schiaparelli that we owe much of our knowledge of its topography. In 1877 he announced his famous discovery of the "canals" on Mars, more correctly translated "channels," for "canals" are too suggestive of waterways; indeed the American astronomer, Pickering, doubted the presence of any water in them. There

has been much speculation as to the nature of these "canals," some going so far as to regard them as artificially constructed by Martian engineers! These fanciful ideas, however, are dispelled by the impartial scrutiny of photographs involving large telescopes, though it is still uncertain whether the canals are real or partly subjective appearances. Mars has a thin but distinct atmosphere, and both water vapour and oxygen have been identified in it. The equatorial temperature would appear to be something like that of a cool bright day on the earth, ranging between 45° F. and 65° F. But it must begin to freeze at the equator when the sun sets, and at higher latitudes even the day temperatures are not much above freezing-point. There are thin apparent snow caps at the poles, which can be seen to shrink or grow alternately as the summer or winter season advances in the respective hemispheres. On the whole, it may be said that the existence of life on the planet is quite possible—at least, we know of no conditions that would render it impossible.

Has Mars a satellite? Up till 1877 the answer was in the negative, but in that year Asaph Hall detected two minute squire attendants on the "war planet," and it says much, not only for Hall's powers as an observer, but also for the excellence of his instruments, that these bodies were detected at all, for Phobos is only thirty-six miles and Deimos ten miles in diameter. The existence of these tiny moons was confirmed by Lowell in 1894.

Jupiter.—Turning now to the great planets, What has been learnt about them since the middle of the last century? Jupiter was the first to claim attention, and, in 1870, the English astronomer, Proctor, regarded it as a "still glowing mass, fluid probably throughout, still bubbling and seething with the intensity of the primeval fires, sending up continually enormous masses of cloud to be gathered into bands under the influence of the swift rotation of the giant planet." Jupiter on such a view must be regarded as half sun, half world, and this interpretation of its structure is that now generally held. Jeffreys, 1923, advanced another theory which regarded Jupiter as "cold and solid," but this view has not been received with

general approval. The most striking features about Jupiter are its great cloud belts and the so-called "red spot," a large area which has been under observation for fifty years. These features, however, are not constant, owing to the violent turbulence of Jupiter's atmosphere.

Such turbulence probably betokens a very hot interior, causing violent convection and enormously deep clouds, the cold tops of which we see as the planet's surface. The temperature of the latter is certainly very low, about $-170°$ C. This does not necessarily preclude a hot interior (see p. 360).

The likeness to the sun was strengthened when, in 1865, Zöllner showed that Jupiter rotates more rapidly at the equator than towards the poles. Moreover, Jupiter and his satellites, in their general relations, constitute an almost complete replica of the sun and planets—the solar system on a tiny scale. Since the time of Galileo it was known that Jupiter had four moons, one nearly as large as Mars; but in 1892 a fifth satellite was discovered, only 100 miles in diameter, and again, in 1905-6, four others. This system of satellites resembles the planetary system, in the sense that the more massive members are found in the middle of the series.

Saturn, Uranus and Neptune.—Saturn also has numerous satellites, and eight of these were known before the middle of the nineteenth century. The ninth was discovered in 1898 and a tenth in 1905, although there is still some doubt as to the existence of this last. The ring system that puzzled Galileo so much has now been resolved into three concentric ribbons of discrete meteoritic particles, each a tiny satellite.

Very little has been added to our knowledge of Uranus, which is known to have four relatively small satellites all revolving in nearly circular orbits, but in a direction *retrograde* to that of most planetary objects (which move from west to east, like the sun itself about its axis). This reverse direction of motion is also found with one of the minor satellites of Jupiter and one of Saturn.

Neptune, about which also little is known, has only one,

relatively large, satellite, but it too moves in a retrograde direction.

All these outer planets are very light and bulky objects, Saturn especially, whose density is only 12 per cent. of that of the earth, which is the densest planet. From this it may be supposed that these giant planets are in a semi-gaseous condition—that, in fact, they are very hot within, and owing to their large size have not cooled down to the same degree as the smaller planets. More will be said about this when we come to consider the earth's atmosphere (pp. 359-363).

New Planet, Pluto.—In 1915 Lowell predicted the existence of a small trans-Neptunian planet, which would have a mean distance from the sun 43 times that of the earth, and a mass $6\frac{1}{2}$ times that of the earth; he also predicted its orbital eccentricity and position. The calculations were similar to those of Le Verrier and Adams, which led to the discovery of Neptune, but much more intricate, as the perturbation data were on such a small scale. Pickering in 1919 made a similar prediction, as well as others, but their conclusions were quantitatively different.

On January 21, 1930, a photograph was taken at the Lowell Observatory, Flagstaff, Arizona, which apparently indicated the suspected planet, and after seven weeks' observation, on March 14 Shapley announced that this object, whose brightness was only of the fifteenth magnitude (see p. 329), conformed fairly closely to Lowell's hypothetical planet.

It is, of course, too early as yet (April, 1930) to be certain, but if, as it appears, the orbit of Neptune no longer "marks the frontier of our solar system" and this is a new planet, its discovery will open up an interesting field of work for mathematical astronomy. Its insignificant brightness would seem to indicate that it is so cold as to have no clouds, and if when hot it originally had an atmosphere the gases would be in a liquid condition by now, seeing that it must have cooled down and can receive practically no heat from the sun. Moreover, its distance shows that like Neptune (p. 88) it does not conform to Bode's law, for if it did, the distance would be about 73 times that of the earth. Further particulars will, of course, be awaited with great interest.

Comets and Meteors.—With regard to the other permanent or occasional members of our solar system we need say little. Meteors and comets are generally acknowledged to belong to one and the same category; in fact, a comet "is simply a swarm of meteoritic particles more or less closely packed together," and Schiaparelli, in 1873, said that "the meteoric currents are the products of the destruction of comets, which is brought about by the action of the sun and planets on the different particles composing the heads of comets which are thus drawn into different orbits."

The Stars and Nebulæ.—But advances in our knowledge of the members of our own solar system, important as they have been, are insignificant as compared with what we have learnt about the universe beyond what Lucretius called "The glittering ramparts of the world." Astronomers are now armed with instruments that were quite unknown to their predecessors of last century. The photographic telescope has revealed the existence of stars and nebulæ in the depths of space undreamt of a hundred years ago. Herschel estimated that he could see five and a half million stars, but now some 1,500 millions have been photographed, and yet the limits of the universe—if it has any limits—seem far from having been reached. Halley knew of only six nebulæ, and Herschel catalogued 2,500; now we know some two million. Again, the spectroscope has entirely altered our outlook on the heavens. By its means we are able to analyse the chemical nature of the faintest star almost as easily as we can some unknown substance in a chemical laboratory; we can estimate the velocity of its movements, the pressure of its atmosphere at different levels, its temperature, as also its distance from us. To explain how all this is done, and to give even the merest outline of the results obtained, would require far more space than we can afford. We must content ourselves with glancing at three aspects only of stellar research—viz., the distance of the stars from us and their size, the amount of heat they radiate, and their chemical composition. To give us this information we require three instruments over and above the telescope; these are the interferometer, the radiometer and the stellar spectro-

scope. In describing them we will borrow from the excellent and beautifully illustrated manuals written by Professor G. E. Hale of Mount Wilson observatory, where there are to be seen probably the very finest astronomical instruments that ingenuity can devise and mechanical skill can produce, backed by unlimited monetary resources.

The Interferometer—MICHELSON.—So far as the size and distances of the stars are concerned, the name that stands out most prominently in connection with these subjects is that of Albert A. Michelson, who invented the interferometer. The following is a condensation of Hale's description of this instrument given in his book "The New Heavens."

Make a narrow slit, a few thousandths of an inch wide, in a sheet of black paper, and fix it vertically in front of a bright light. Observe the slit through a telescope capable of magnifying about thirty times, placed at a distance of 40 to 50 feet. The object glass of the telescope is provided with an opaque cap—pierced in the horizontal plane by two circular holes, each about $\frac{1}{8}$ inch in diameter, and each about $\frac{1}{4}$ inch on either side of the centre of the cap. When the cap is off, the slit will appear as a narrow band with much fainter bands on either side of it; when the cap is on, the central band will appear as if ruled with narrow vertical lines or "fringes," which are produced by the interference of the two pencils of light coming through the object glass from the distant slit. Cover one of the holes and these fringes at once disappear. Let the two holes in the cap be made in movable plates, so that their distance apart can be varied. When the holes are gradually separated the fringes become less and less distinct, and finally vanish. Measure the distance between the holes and divide this amount by the wavelength of light, say $\frac{1}{50000}$ inch, and the result is the angular width of the distant slit, and knowing the distance of the slit, its linear width may at once be calculated. To measure the diameter of a star the same procedure is followed, but since the angle it subtends is so minute, a very powerful telescope is required fitted with a very long interferometer, because the smaller the angle the further apart must be the holes over the object glass.

Let us take a definite case. In the southern sky in winter there is one very prominent and easily recognised constellation—viz., Orion. Its essential features are indicated in Fig. 104, but no detailed description need be given, for we are concerned with only one of its stars, "Betelgeuze," whose name is Arabic for "Giant's shoulder." The interferometer used at Mount Wilson was 20 feet long, and was mounted on the great 100-inch Hooker telescope. The plan of the instrument is shown at Fig. 103. The light from the star, S S, is received by the two movable mirrors, 1 and 4, which correspond to the two holes in the cap of the telescope above described. These rays are reflected to the mirrors, 2 and 3, and thence to the concave reflector, 5, at the bottom of the telescope tube, from which they are again reflected to the convex mirror, 6, then to the plane mirror, 7, and thence to the eyepiece, E, where the fringes are observed under a magnification of 1,500 to 3,000 diameters. On examining "Betelgeuze" with this instrument the fringes disappeared when the mirrors were 10 feet apart. Without giving the actual calculations the result was that the angular diameter came out at 0·047 of a second of arc, or, to give a homely parallel, it was what a ball 1 inch in diameter would look like at a distance of seventy miles! To know the linear diameter of "Betelgeuze," however, we must know its distance, which may be estimated from its parallax (p. 74). The parallax was found to be 0·02 of a second of arc—*i.e.*, the angle subtended by the radius of the earth's orbit at the distance of "Betelgeuze." This would make the diameter of the giant at least 100 millions of miles, or more than 100 times that of our sun, and its distance from us at least 160 light years (see p. 320). In other words, light travelling at 186,000 miles a second takes 160 years

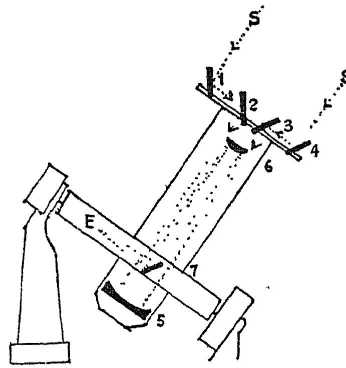


FIG. 103.—INTERFEROMETER. (After HALE.)

to cross the space between "Betelgeuze" and the earth, so that the light we see now left the "shoulder of Orion" a few years after Prince Charlie landed in Scotland!

A "light year" is a convenient astronomical unit of distance, and being the distance covered in a year by light travelling at 186,000 miles a second, so is $186{,}000 \times 60 \times 60 \times 24 \times 365$ miles ($5 \cdot 9 \times 10^{12}$). "With the naked eye," writes Professor Eddington ("Stars and Atoms"), "you can see the Andromeda Nebula as a faint patch of light. When you look at it you are looking back 900,000 years into the past." The "depths of the universe" are truly appalling.

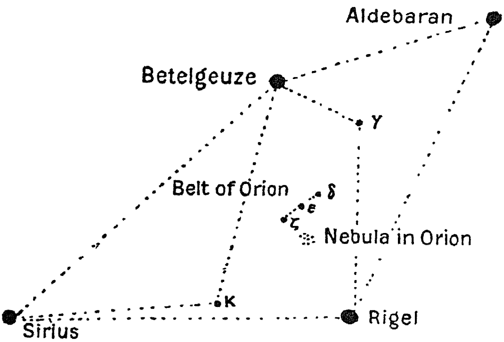


FIG. 104.—BETELGEUZE AND THE CONSTELLATION OF ORION WITH ADJACENT STARS.

By its parallax "Sirius" (Fig. 104), the brightest star in the heavens, is estimated to be about eight and a half light years distant, and there are only three other great stars nearer to us than "Sirius." But even "Betelgeuze" is a near neighbour as compared with some of the 1,500 million stars photographically observed, and many nebulæ are known to be as much as millions of light years away! A better idea of these distances will be gained later when we consider stellar evolution and astronomical space and time (p. 338).

The Thermocouple and the Radiometer — HUGGINS, LEBEDEW, NICHOLS.—To be able to measure the size and distance of a star is indeed a great feat, but to estimate the heat it gives out would seem an absolute impossibility—and yet it has been done. Sir William Huggins (1824-1910) was the first to make the attempt. He was a pioneer in astro-physics by bringing into use, in astronomy, all suitable appliances from the physical laboratory. One of these was the thermocouple, a conjunction

of two metals which were very sensitive to radiant heat. The principle of this apparatus will be understood from Fig. 93. Solder together an iron and a copper wire, and connect the free ends with a galvanometer (Fig. 105, G). When heat is applied to the junction of the wires, the needle of the galvanometer at once shows a deflection, indicating that a current is passing through the wires, and the amount of the deflection shows its strength and indirectly the degree of heat affecting the couple. Huggins, in 1869, attached such a couple to his 8-inch telescope, but although he thought he got an effect, his results were not confirmed. In 1895 the Russian physicist, Lebedew, invented a much more sensitive thermocouple made of iron and constantan (an alloy of copper and nickel), with which positive results were obtained a few years afterwards. Complete success, however, rewarded the use of a new radiometer, invented in 1898 by the American physicist, Nichols. This instrument consisted of exceedingly delicate vanes of mica suspended in a vacuum. These vanes received the stellar rays reflected from a 24-inch concave mirror, the degree of deflection being observed through a small auxiliary telescope. Hale gives the following illustration of the sensitiveness of the apparatus. It was found that the average deflection of the vanes induced by a candle 2,000 feet distant was 67 mm. Nichols's assistant, who was in charge of the light, blew it out at a given signal, and inserted his own head in its place, when the deflection given by the radiometer was 25 mm. This experiment was tried again and again, so that blood-heat, even after absorption by the intervening air, could be registered at a distance of nearly half a mile!

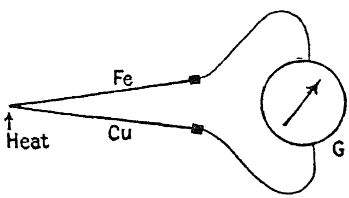


FIG. 105.—A SIMPLE THERMOCOUPLE.

When the radiometer was used along with the 100-inch Hooker telescope at Mount Wilson, it was found possible to get quite astonishing results. The average deflection given by the star "Arcturus," whose diameter is 21 millions of miles and whose distance from us is estimated to be not less than

thirty light years was 1·08 mm. Thousands of observations of this kind have been made during the past few years, both with Nichols's radiometer and also with greatly improved thermocouples, and from the results obtained astronomers tell us that "the redder the star the greater the proportion of invisible heat radiation it sends us." A red sun like "Betelgeuze" has a surface temperature of 2,500° to 3,000° C., and its density is exceedingly low, but in the centre the pressure is higher, and the temperature is as high as 2 to 3 million degrees. Such a star radiates out heat on a gigantic scale, but it will decrease in diameter and waste slowly away, while the temperature will imperceptibly rise as the star changes from red to yellow and then to white. The surface temperature of a white star may exceed 20,000° C., and its central temperature may exceed 100,000,000° C.! In the heavens we have presented to our gaze every variety of stage in stellar evolution, as we shall see presently; and in this orderly sequence, or, as it is sometimes called, Celestial or Inorganic Evolution, we thus have giant red stars at one end of the scale and dwarf white or red ones at the other. Our own sun, as we have seen, is on the way to become a dwarf star and has a surface temperature of about 6,000° C. with a central temperature of approximately 30,000,000° C. (Hale), or 40,000,000° C., according to Eddington.

All stars by radiating energy copiously must be losing mass, matter being as we have seen (p. 269) a stupendously concentrated form of potential energy. So according to the latest theory of Cosmogony put forward by Jeans, the sun and indeed most of the stars are mere fragments of the massive giants they once were. And so he explains the sun's continued output of energy, maintained over millions of millions of years, by the annihilation of material atoms and transformation of matter into radiation.

The Spectroscope and Spectrum Analysis.—When, in 1868, Lockyer discovered the element helium in the sun, he opened up an entirely new chapter in astronomy—viz., the chemical analysis of the stars by means of the spectroscope. We have already seen (p. 164) how helium was isolated by Ramsay

from a terrestrial mineral nearly thirty years afterwards, and the extraordinary part of the story is that this new element should have been found in a stellar body 93 millions of miles away, long before it was discovered at our own doors.

During the past fifty years our knowledge of the chemistry of the stars and nebulæ has been vastly extended, and, while no strange elements have been discovered (unless we include the hypothetical "coronium" in the solar corona), many of the terrestrial elements appear to be missing in several of the stars that have been analysed. To take the case of our own sun, the following elements have been identified in it by the aid of the spectroscope: hydrogen, oxygen, calcium, iron, sodium, carbon, magnesium, cobalt, aluminium, chromium, strontium, manganese, copper, zinc, cadmium, silver, tin, lead, potassium and others; but, strange to say, some elements of immense importance to us on the earth are apparently entirely absent, such as sulphur, phosphorus, mercury, gold and nitrogen. Still, it is possible that by adjusting the intensity of the spectrum some of these may yet be found. We know that the bright lines of sodium vapour may be made so intensely bright that the spectrum of limelight placed behind the vapour does not "reverse" or turn them into dark lines. If the sodium lines be made fainter they may be reduced to exactly the intensity prevailing in that part of the spectrum of limelight, in which case the lines would not be distinguishable at all.

There is another use to which the spectroscope has been put in relation to stellar exploration. If we are approaching a source of light the waves will meet us more quickly than if we are stationary, or more slowly if we are receding from it. When we are approaching, the waves will appear shorter, and this is indicated by a very slight shift of the lines of the spectrum towards the violet end. Conversely, if we are receding, the lines will be shifted towards the red (Doppler effect, see p. 307). On examining "Sirius," we find that same line, F, of the spectrum is slightly displaced towards the red end, and from the amount of that displacement we are able to deduce that Sirius is receding from the solar system at the rate of about 70,000 miles an hour. "Arcturus," on the other hand, is approaching at about

200,000 miles an hour; but seeing that "Arcturus" is thirty light years away we need not feel alarmed, for there is no possibility of a collision for at least a couple of million years, even if the speed and direction towards us were maintained.

Stellar Evolution and Modern Cosmogony.—Great as are the achievements of observational astronomy, they pale before the greater triumphs of the human mind in solving the riddle of the universe by mathematical analysis of the observational results. The names of Einstein, Eddington, and Jeans will ever be associated with these mathematical triumphs; but here, of course, it will only be possible to give the broad outlines of the picture without details. The world owes a debt of gratitude to Jeans especially, and we must now draw freely on his fascinating books (p. 309) to render his conclusions intelligible to enquiring minds. Now the power of Mathematics, especially the calculus, in the service of Science is so wonderful in elucidating what would be otherwise insoluble problems, as to be almost uncanny and scarcely believable to those unacquainted with its intricacies. Every branch of astronomy, involving the interrelationships between time, space, matter, and energy has been submitted by Jeans to such mathematical analysis, and the infinitely complex results have been integrated into a relatively simple picture portraying the Cosmos. By five or six independent methods of approach the age of the Galaxy (p. 312), including our sun, has been determined and found to be about 5 to 6 million million years, and prior to this it existed as one vast rotating gaseous nebula, similar in almost every way to the 2 million nebulæ (outside our system) which are scattered in every direction through the known universe.

This single nebula, which gave birth to the galactic system that we call the Milky Way, as a sort of small universe on its own, can no more be explained than can any other nebulæ; but the changes it must have undergone in its history can be calculated, and they are found to be similar to what is happening now to the extra-galactic nebulæ. Briefly speaking, the sequence of changes involved were (1) contraction with increasing speed of rotation, and consequent flattening from an

approximately spherical shape to that of a lens, (2) eventual instability when the speed of rotation exceeded a certain critical limit, gaseous matter being then ejected from the sharp edge in the form of two oppositely situated equatorial arms, as a kind of spiral.

This spilling out of incandescent gaseous matter by centrifugal effect was, of course, on a stupendously vast scale, comparable in dimensions to that of the Galaxy as we know it now (see below for dimensions), but otherwise similar to that conceived by Laplace (p. 84) on an infinitely smaller scale for the origin of the solar system.

Ultimately the whole nebula was dispersed in this way, and the shed equatorial matter became subject to what is called gravitational instability, which led to the formation of centres of condensation, as vast and heated globes of gas, destined to become independent stars by further shrinkage. Stars, then, are to be regarded as "drops" or points of condensation, which have formed in the jets or filaments thus thrown off horizontally from the edge of the shrinking lens or disc, giving the present plane, in fact, of the Milky Way.

The number of such stars, so born out of our parent nebula forming the present galactic system, amounts to anything from 30,000 million (Seares) to 300,000 million (Eddington), though Shapley gives a figure of 100,000 million.

Herschel and (later) Kapteyn were wrong in supposing our sun to be near the centre of the system, and Shapley believes the centre to lie in a massive star-cloud in the constellations of Scorpio and Ophiuchus, 47,000 light-years away from the sun. The confusion has arisen from the fact that near the sun there is a "local system" or great cluster of stars like another galaxy on a smaller scale, lying in a plane inclined 12° to the galactic plane and not in it. This local system is in the form of a relatively small flattened disc, or rather cake, like the great biscuit-like shape of the whole galactic system, which is roughly 220,000 light-years in diameter and 40,000 light-years thick. The sun, which till recently was believed to be only about 2,000 light-years from the centre of the Galaxy, is now believed to be about twenty times this distance

away, slightly to the south of the horizontal plane of the Milky Way.

The movements of the multitudinous stars in this immense system were first detected by Kapteyn in 1905, in the form of two distinct star-drifts, and these movements have been very difficult to disentangle. But, generally speaking, it has been found that in addition to a lot of independent motion of groups of stars and individual clusters like the Great Bear, Pleiades, etc., there is a general movement of rotation of the system as a whole round the centre, one revolution occupying some 300 million years. This conclusion is based mainly on the work of Oort and of Plaskett; and it is interesting by way of comparison to observe that the period of revolution of the Great Andromeda Nebula is of the order of 19 million years.

This *relatively* near nebula seems to be a counterpart of our own galactic system, of which it is independent, at an immense distance away (about 900,000 light-years); but it is at an earlier stage of evolution—namely, at the stage in which stars are being born in its outside regions, while the centre is still in a gaseous condition. It has a distinctly spiral shape, illustrating how matter is being flung off at the equatorial regions; it is flattened; and its total mass, according to Hubble, is equivalent to 3,500 million suns. There are, as already stated, something like 2 million such nebulæ (though not so near and conspicuous as the one in Andromeda) scattered throughout the visible universe, and they show every gradation in the evolutionary sequence, from spherical gaseous masses, through flattened figures spilling out equatorical matter, to nearly finished configurations of stars like "island universes," similar to our own Galaxy.

Turning to the individual stars of our own system, we find they are much more crowded together near the centre (though relatively at enormous distances apart from each other, on average), but thin out considerably as we approach the outer confines of the Galaxy. The near stars, which are mostly visible to the naked eye, and amount only to a few thousand, belong, of course, to our own system, as do the vast numbers revealed by telescopic photography. Among these there is immense variety as regards size, temperature, and

luminosity, but not such great variety in mass. Most of them, indeed, are somewhere about the sun's mass, and for the vast majority the extremes are between $\frac{1}{10}$ and ten times the sun's mass. It is true that there are a few stars, like Plaskett's star, sixty or seventy times the weight of the sun, or even more, but the variation in size and luminosity is much more extreme. The diameter of Antares, the largest known, is 450 times that of the sun, and van Maanen's star, the smallest known, less than $\frac{1}{100}$ that of the sun, so that the latter is actually smaller than the earth. But this dwarf has a surface temperature of 7,000° (*i.e.*, greater than that of the sun), and its mass appears to be about that of the sun, so that it must have an enormous density, the reason for which has already been considered (p. 310).

In respect of luminosity, the greatest known is that of S. Doradus in the Magellanic Cloud, 300,000 times that of the sun, sufficient indeed, if it were in the sun's position, not only to scorch the earth but to raise its temperature to 7,000° C. and so convert it into a globe of gas. At the other extreme is the star Wolf 359, whose luminosity is only $\frac{1}{50000}$ that of the sun.

In general, however, most of the stars must be regarded as very similar to the sun, consisting, like it, of an internal liquid core of atoms, more or less completely stripped of electrons, and an outer gaseous envelope, the surface of which, only, lends itself to observation. The liquid core of some stars must have a rapid speed of rotation, and it is possible to calculate what will happen when this speed increases, as it must by contraction following the stripping off of successive rings of atomic electrons, as already explained.

Binary Stars.—The behaviour, then, is very different from what it is with a rotating mass of gas like a nebula, where most of the mass is concentrated towards the centre. Instead of developing a flattened or lens-shaped form, which is calculated for such a case, and which must spill out equatorial matter from its edge by any increase in rotation, a spherical rotating liquid mass, whose speed of rotation increases, must pass through a different sequence of changes in form. This sequence commences in a flattened or orange shape (pseudo-spheroid), and by further

increased speed develops into a pseudo-ellipsoid form, which is an elongated shape having three unequal axes. When the latter reach the critical ratio 23 : 10 : 8 increased speed of rotation lengthens it to a cigar shape, then develops a furrow or waist, somewhere towards the middle, when the length is about three times the width. After this the mass begins to concentrate at each end, something like a dumb-bell, the furrow deepens till it finally cuts the body into two detached, nearly spherical, masses which then continue to rotate about the common centre of gravity, lying on a line joining their centres. As a rule, the two masses are not equal, but they are more nearly so than in the case of the earth-moon system.

In this way binary stars have been formed, and as time elapses they get further and further apart, owing to influences which we need not consider here, but they still continue to revolve around their common centre of gravity. Those stars which have recently suffered fission in this way cannot be distinguished as separate objects in the telescope, but they may, by getting in each other's way, cut off periodically a certain amount of light we receive from them, and thus appear as variable stars (eclipsing binaries) like Algol in the constellation of Perseus. Or they may be detected by the fact that while one is approaching us in the line of sight, the other is receding, and this (Doppler effect, see p. 323) may be detected in the colour of the spectral lines (spectroscopic binaries).

Those binaries which are not too distant from us, or which have moved far apart, may be detected easily by the telescope and their mutual orbits traced out; thus the pair of α-Centauri (A and B), which is the nearest binary, has a period of about seventy years, and a complete orbital revolution has already been mapped out.

Cepheids.—According to Jeans, the so-called Cepheid variables, which are very peculiar in their spectroscopic behaviour, are stars whose liquid cores rotate so rapidly that they are just on the verge of fission, but this view is not as yet generally accepted. His theory is that the liquid core ploughs round and round at such a speed as to throw up a steep and moving wall or wave of hot gaseous matter, in the surrounding

envelope, at short regular intervals. The speed of this moving wave, which occasions the periodicity in light-fluctuation, must be prodigious, since the period is only of the order of a few hours or days, and as the Cepheids are very large stars this would mean a condition bordering on fission. Whether this theory is accepted or not, it is certain that the periodicity in the luminosity is somehow connected with the brightness, that is to say with the real brightness or so-called "absolute magnitude." It must not be forgotten that the ordinary or so-called "visual magnitude" must depend on distance as well as real intrinsic brightness, and for two stars of equal brightness (*i.e.*, identical absolute magnitude) if one were twice the distance of the other its luminosity would be only one quarter (law of inverse squares, which holds for all radiation), and so the visual magnitude would be much higher.*

In 1912 Miss Leavitt of Harvard found that in all cases the visually brighter Cepheids fluctuated more slowly than the fainter ones. Now since the distance of the nearer ones could be measured by the parallax method, this fact could be utilised for measuring the distance of clusters containing Cepheids beyond the limits of the parallax method, by building up as it were a measuring-rod and step by step plumbing farther and farther into the depths of the universe—viz., on the basis that equal period means equal intrinsic brightness, and so the observed visual magnitude gives the distance by the law of inverse squares.

In the hands of Herzsprung and Shapley this elegant method has opened up vistas of such immense distances that it is at last possible to construct a rough sort of model of the universe

* As bright stars are said to be of the first magnitude (visual), it follows that those stars of second magnitude, etc., are not so bright. Stars of the fifth and sixth magnitude are very faint to the naked eye. As a matter of fact, the brightness increases two and a half times for every step down in magnitude, so that in the five steps from the sixth magnitude to the first there is an increase in brightness of no less than 100 times. In astronomy, fractions of a magnitude are employed, also minus numbers to indicate very great brightness; and the "absolute magnitude" of any star represents its luminosity as it would appear at a standard distance of 32·6 light-years. Thus, for example, S. Doradus, the brightest known star, has $Mag._{abs}-9$, Sirius 1·3, and the Sun 4·85.

itself (see p. 340). Returning to the Galaxy, we observe that whilst the vast majority of stars must have followed an evolutionary course similar to the sun, some 20 or 30 per cent. were endowed with a higher speed of rotation and so have gone over into double stars. But all of them are much about the same as our sun in age (p. 309), though vastly varying in luminosity and size; and the only satisfactory explanation of this long continued output of radiation is found in Jean's theory of annihilation of hypothetical types of atoms, higher in atomic number than uranium (see p. 309).

In its early history a star was simply a distended gas balloon, as some of them still are. In this state, as Eddington has worked out, they would be subject to the forces of *radiation pressure* in addition to gravitation, this pressure, negligible with ordinary hot bodies, being of the same order as gravitation at the temperatures in question. Eddington believes this was the principal force at work in causing independent centres of condensation (potential stars) to appear, but Jeans finds that gravitational instability (p. 325) would be sufficient to bring the segregation here, as well as in the formation of the solar system itself, as we shall see later. In any case the gas globes would tend to shrink, but this tendency was, on Jeans' annihilation theory, checked by the great initial output of radiative energy, and on this theory the prime cause of shrinkage was the stripping of electronic rings, as the interior temperature rose by reason of this great output exceeding the loss by radiation at the surface. The evolution, in short, was similar in the majority of cases to that of the sun already outlined (pp. 309-311).

All stars were thus, like the sun, originally more massive and more prodigal in their youthful and wasteful expenditure of energy than they now are, in their old age so to speak; and on this theory it would seem as if the few massive and brilliant giants which still exist, and which may show thousands of times the energy-expenditure of the sun, must be young. If so it is difficult, on the annihilation theory, to account for them as having been born out of the original nebula, along with the majority of the stars. It is possible that they are not young,

but that the matter within them has in some way been preserved from annihilation, in the intervening ages, say by segregation of the nuclei apart from the electrons. Of course, this is purely speculative, but it finds some support in the existence of the so-called "white dwarfs," which, though at an enormous temperature within, are in some way immune from sub-atomic annihilation.

Russell, whose brilliant work on the classification of stars has been of such service in developing these new ideas, does not altogether accept them. The stars are classified according to spectral type, which is really that of surface temperature in the series: O, B, A, F, G, K, M, with divisions 1 to 10 between each letter, representing a type; the O-stars being the hottest (say 30,000° C. at the surface) and M-stars the coolest (about 2,500° C.). Russell's first idea was that M-stars with time got hotter by contraction and passed into the K, G, F, and A types successively, and then by cooling returned along the same sequence in the reverse direction. This theory of an ascending and descending scale of temperature, with the progress of time, was originally put forward by Sir Norman Lockyer towards the close of the nineteenth century in his book "The Meteoritic Hypothesis," but owing to difficulties which need not be considered here the theory cannot be accepted in its original form—*i.e.*, contraction causing temperature increase. In 1925 Russell modified his first views and put forward the theory that when the centres of stars reached a critical temperature of 30 million degrees C. by contraction, matter itself became unstable and annihilated itself with enormous generation of energy. As a result of this great increase in energy the temperature tended to rise above the limit of 30 million degrees C., but by so doing expanded the volume of the star, and so cooled it (adiabatically) below this point of material disintegration. Then, after a time, cooling and contraction would supervene and the cycle repeat itself.

It is true that rhythmic contraction and expansion may take place in some stars, and may account for some of the variables which cannot be explained otherwise. Betelgeuze (p. 322), for example, shows changes of no less than 25 per cent. of its

diameter at regular intervals. Nevertheless there are difficulties of a mathematical kind in the way of accepting Russell's theory, as Jeans has pointed out; but the latter mainly objects to it on the ground that if matter became unstable at some particular or critical temperature, any star where this temperature was attained would become so violently unstable as to resemble gunpowder at its flash point. Here we must leave the problem and pass on to consider our own solar system.

Origin of the Solar System.—The original Nebular Hypothesis, put forward by Laplace (p. 84), was later found, on mathematical examination, to fail to explain the existence of our planetary system, among other reasons, because the centrifugal effect, due to the angular momentum, of the rotating "nebula" from which the system was supposed to have developed, could never have been sufficient to throw off the planets and their satellites.

Thus the angular momentum of the whole solar system (over 95 per cent. of which is due to Jupiter) is only about twenty-eight times that of the sun, and if it were put back into the sun the latter would rotate at a speed of about once in 24 hours, which is a much lower speed than that of Jupiter (about 10 hours), which holds together. On the other hand, if the sun functioned as a gas with most of its mass concentrated in the centre, it is possible with a high speed of rotation to assume the lens-shaped figure which we saw (p. 325) preceded the equatorial disruption of nebulæ, but in this case it can be calculated that 85 per cent. of the mass would have to be at the centre. Now, of course, this seems impossible on the older views as to the sun's constitution, but on Jeans' theory of "liquid stars" it is conceivable; but even so, by a theorem of Poincaré it can be shown that ejected matter from the equatorial edge of a lens-shaped figure would have to possess a higher density than is possible for the planets, if it were not to scatter away into space by its own internal pressure. Further, there would be the difficulty of explaining how the sun ever got back from such a figure to spherical, how the satellites could have formed from scattered matter, as well as other difficulties.

Towards the end of the nineteenth century Lockyer put forward the Meteoritic Hypothesis, by which the stars and the solar system were supposed to have been evolved from the gravitational clashing of small cosmic particles or meteorites, which are certainly very numerous in space; but this view meets with grave difficulties on close examination and has not been accepted.

A more recent attempt is the Planetisimal Hypothesis of Chamberlin and Moulton, in which the tidal effect on our sun is invoked, raised by a star which at one time passed very close to it. There is no doubt that the enormous tides which would be so raised, on a rotating ball of practically gaseous matter, could cause such disturbances as to produce eruptions of superficial material on the side nearest the star, as well as on the opposite side. On this hypothesis, this ejected matter, in the form of fine particles or planetisimals, revolved round the sun in many orbits and eventually coalesced into a comparatively few globes of matter which are now planets and satellites.

A modification of this hypothesis has recently (1924) been put forward by Jeans, who has mathematically examined the whole problem of planetary evolution in a most exhaustive manner, taking into account all the known facts elucidated by modern research. Let us consider this hypothesis.

We have seen how millions of stars can be born out of a single gaseous nebula whose mass is mainly concentrated in the centre. The sequence of shapes arising from increase in rotation, with such gaseous masses, is very different from what it is in the case of rotating liquids (see p. 327); the calculated sequence for gaseous nebulæ begins, as with liquids, with a spherical followed by a flattened spheroidal figure, but this later assumes a flattened lenticular shape with a sharp equatorial edge. When this critical figure is reached any further increase in speed of rotation must lead to instability, and it is this instability that causes the shedding of filaments of matter, spilling out as the spiral equatorial arms as we have seen on p. 325, and giving birth to stars by local condensations. Moreover, such local condensations, denoting stars or clusters of stars in process of

birth, are telescopically visible in the nearer extra-galactic nebulæ, and every stage in the evolutionary process, from spherical to spiral nebulæ in process of disruption, has been observed in different parts of the universe. Each of these numerous nebulæ is comparable in mass to that of our own galactic system, which it is supposed has already gone through such an evolutionary process about 5 to 6 million million years ago.

Up to this point mathematical theory and observational astronomy are in harmony. Difficulty only arises when the further evolution of each independent star is considered; for mathematical investigation shows that, instead of planetary systems being developed, the normal course is for the star either to remain a single spheroid or to split into two (binary stars), as the star contracts and thereby increases its speed of rotation. In no case does it appear possible for matter to be detached equatorially and form planets on the lines of our solar system, and so there must be something rather exceptional about our sun and his family of planets. At this point Jeans admits that exact science ends and speculation begins, but he postulates that the only conceivable explanation of the anomaly is the chance encounter, at one time, of our sun with another star. With the present distribution of the stars in space, the probability of such an encounter is too remote to consider seriously. Our nearest neighbour at present, for instance, Proxima Centauri, a tiny but massive dwarf near the α-Centauri pair (p. 328), is twenty-four million million miles away, and even if it were only a small fraction of this distance away its tidal influence on the sun would be negligible. And the theory of probability shows that since the beginning of things insufficient time has elapsed (say within the last six million million years, which is approximately the sun's age), for such a star to come within the critical distance necessary to pull tidal matter out of the sun. But this is supposing the present average distance of the stars of the Galaxy has not sensibly altered, and the difficulty would be met if it were assumed that, at one time, the concentration of stars in space near our sun was considerably greater than now. There

is *a priori* probability for this assumption, with its increased chance of an encounter by which such a cataclysm might have happened. That is to say, some neighbouring star, wandering by, came very close to our sun, not close enough for a collision or even close enough to interfere with the independent career of each, but nevertheless within that critical limit (which can be calculated for different sizes and masses) necessary to pull tidal matter out of our sun. This distance must have been something between one and two solar diameters, and the wandering star must have performed a curved journey (owing to mutual gravitational attraction) towards and from the sun, in a plane inclined some 6° or 7° to the sun's equator. This plane, now the plane of the ecliptic, is that in which the main planetary mass now moves round the sun, the latter having continued to rotate round the same axis as before the cataclysm. There seems to be every reason to believe that this must have all happened within a short space of time, about two to three thousand million years ago. This, of course, is but yesterday compared with the great age of the sun, and in the encounter with the stranger, it is just as if our solar mother had mated, after a barren life of fifty years, and only a week ago given birth to a family of lusty planets in a single litter. It is now possible to picture how this birth, which is so recent an event in astronomical time, took place.

As the star approached nearer and nearer, the solar tides grew ever higher and higher until at last when the critical distance was reached, the tidal matter ceased to fall back completely, the sun's gravitational attraction being just balanced by the centrifugal force and star's attraction. As the star got nearer a jet of half-liquid, half-gaseous matter streamed out from near the sun's equator. This jet or filament, like a moving spiral, increased in amount and thickness as it was payed out, being fully gaseous during near approach, but it diminished in amount and soon became mainly liquid as the disturbing star passed away. This stupendous torpedo-shaped coil of matter, massive but gaseous in its middle, was meantime forming its own centres of condensation and rotation, and later at most centres a similar process repeated itself on a diminutive scale, thus

eventually giving rise to the satellites, circling round their primaries, and revolving in the same direction.

The exact mode of these condensations into potential planets and satellites is beyond the power of mathematics to unravel. But the first condensations must have occurred, according to Jeans, almost at once, owing to gravitational instability (see p. 325) while they were under the influence of both sun and stranger, and were still for the most part very hot and gaseous. Jupiter and Saturn must have reproduced the solar cataclysm almost exactly, but, of course, on an immensely smaller scale; but their satellites did not repeat the process, because they were so small as to cool down quickly and so become liquid. And so there was a limit to the birth process when grandchildren were born.

At the thin ends of the original filament the rate of cooling must have been very rapid, and so the condensation centres here quickly became liquid planets. The disruption of spherical liquids under tidal influence follows a very different course from that shown by gases. It can be shown mathematically that excessive tidal forces first elongate the sphere to a long spheroid, which then furrows at one end, giving a pear-shaped figure. This finally develops a bulb at the narrow end, and suffers fission, giving a detached mass (satellite) which is relatively much more massive in comparison to the total weight, than that in the case of tidal disruption of gaseous figures.

It is very probable that some tidal influences causing the detachment of satellites from their primaries were induced by our own sun after the stranger had passed. For the orbits of these primaries, or potential planets, would be exact ellipses, and there would be so much mutual disturbance that these primaries may in their early existence have come very close to the sun in perihelion passage. But the whole region of the solar system must have been so full of scattered debris and light gases, which had escaped, the planets having to plough their way through this resisting matter, that their orbits would gradually become more circular. In any case most of this scattered debris must have been picked up by the planets, the rest having escaped into outer space; but the

zodiacal light in the neighbourhood of the sun shows that there is some of this cataclysmic material still left as witness of the great event of those far-off days.

At all events, when the wandering star had passed away, all this incandescent matter, no longer subject to outside interference, settled down to form globes and satellites, now subject to the sun's influence, and cooling down to form the planets, etc., as we know them today. Those like Neptune and the earth which were born more or less liquid have, as they ought to, few (one each) but large satellites, those like Jupiter and Saturn which were born wholly gaseous have relatively many but small satellites (because they were born bulky). Mars was born gaseous, but being towards the thin extremity of the gaseous filament it was not massive enough to hold itself together; that is to say, because the kinetic energy of the gaseous matter at high temperature (p. 224) was superior to the gravitational potential most of it has been dissipated off into space, and the same is true (for the same reason) with Uranus, which was originally much larger than it now is. The inner planets Venus and Mercury were born liquid at the thin extremity of the filament, and they were apparently unable to cast off satellites.

It only now remains to consider the Asteroids and Saturn's rings. These offer no difficulty when it is considered that tidal influence, being the effect of differential gravitational attraction on the opposite sides of any mass, becomes relatively very great when the attracting objects are near. There is a critical distance known as "Roche's limit," below which any large solid mass like a satellite approaching its primary must be torn up and broken into fragments by the differential forces at work. Roche's limit is a distance from the surface of the primary about twice to three times the radius of the latter, depending on the density of each object. For example, if the moon approached to within 12,000 miles of the earth (as it will do eventually, if nothing intervenes to prevent its present recession to its limit in 50,000 million years followed afterwards by slow approach to the earth), it would be broken up into a mass of minute fragments which would then circle

independently round the earth as a single ring, something like Saturn's. The innermost satellite of Jupiter is already dangerously close to the Roche limit and may break up at any time. The innermost satellite of Saturn has already done so (probably in the early days when there was more irregularity), splitting into three rings instead of one, because of the influence of the other satellites, which make the spaces between the rings an unstable orbit for any satellite.

And the Asteroids probably represent a planet which has been disrupted in this way, owing to the fact that in its early history, when planetary orbits were more eccentric than they are now, this planet wandered into the danger zone of the Roche's limit of Jupiter (or the sun) and so met its untimely end.

Also, according to Jeans, the new trans-Neptunian planet (p. 316) may represent the extreme tip of the original cigar-shaped filament and thus be the first to cool down and solidify; "as a consequence of this it will probably prove to be unattended by satellites." Such in brief is the bold and daring conception envisaged by Jeans to explain the existence of the solar system. It is not susceptible of scientific proof, but, as he says, with this conception "the pieces of the puzzle begin to fit together in a very gratifying manner."

Astronomical Space and Time.—In dealing with space on the grand scale of the universe difficulties are encountered which have presented themselves to all philosophers, indeed, to everyone who thinks and tries to imagine where space ends or when time began. These difficulties arise mainly from a sort of instinctive feeling in the human mind that space must go on for ever, and that time is an independent thing which flows on for ever. This, the Newtonian system of philosophy, received a rude shock when Einstein introduced his conception of relativity, which, as we have seen, identified time and space in one comprehensive continuum, in which a mathematical time-function appears as a fourth dimension, inseparably bound up with the three dimensions or directions (length, breadth, and height) of distance, dimensions which we ordinarily keep separate in our minds and call space.

According to relativity this separation is quite artificial,

even if it is convenient in dealing with the things of ordinary experience, but it breaks down completely when astronomical magnitudes are in question. Relativity, the theory of which has received experimental verification on every issue that can be so tested, tells us that astronomical space-time is not infinite but rather unbounded. It is so in the same kind of way that the earth's surface has no beginning and no end, but returns upon itself without being infinite in extent; and if this idea of the curvature of the space-time continuum is accepted it means that light from the stars does not travel outwards in every direction, but curves round the universe and returns on itself. It means, for example, that if at midnight we pointed a telescope, sufficiently powerful, to a point in the sky opposite the sun, we should see it as a faint star shining with the light it emitted 500,000 million years ago, this being the time calculated for light to travel once round the universe (Hubble).

The universe is so vast that figures denoting dimensions convey little to the imagination, and even when distances are expressed in such large units as light-years (p. 320), the figures are too big to really comprehend. Outside our own galactic system, which occupies an insignificant fraction of the whole of space, there are 2 million nebulæ, visible in the great 100-inch telescope, spaced more or less evenly at an average distance apart of about 2 million light-years, and the most distant is about 140 million light-years away. When the new 200-inch telescope is ready in a few years, we should be able to penetrate twice as far into space and see 2^3, *i.e.* eight, times as many nebulæ if they are there, which would bring the total to 16 million. But it may be that, instead of opening up new fields as we explore farther and farther, we should simply see the nebulæ which are nearest to us over again—namely, by the light they emitted 500,000 million years ago, and which had travelled by the roundabout way instead of direct to us.

It has, in fact, been seriously suggested that the back view of the Great Andromeda Nebula, as it was this long time ago, is now visible to us in the form of the faint nebula *h* 3433 at the opposite side of the sky, that the latter is the same nebula seen by light which has travelled the long way round the universe.

This startling idea must, of course, not be taken seriously till there is more evidence, but there is certainly something strange in the behaviour of very distant nebulæ. In order to make this more intelligible, let us adopt Jeans' model of the known universe based upon proportionately reducing everything in it to a size that we can comprehend.

Imagine, then, the sun as a scarcely visible speck of dust, and the earth's orbit around it (about 190 million miles diameter) the size of a pinhead; our nearest neighbour (Proxima Centauri) is then 225 yards away and the whole Galaxy about the size of the American Continent. Now let us try and explore extra-galactic space. We must travel 30,000 miles to reach a nebula, and then in all directions we find nebulæ, about 30,000 miles apart, till we get a total of 2 million of them. Our model universe has now expanded so much that, in it, you can go about 4 million miles in every direction before you reach the limits accessible to the 100-inch telescope; and each of the 2 million nebulæ represents an "island universe" of thousands of millions of stars, either formed or potential as imperfectly segregated gaseous matter.

Yet space is so empty of matter that even in its most congested regions in the centre of the Galaxy there are not more than six specks of dust for a volume as large as Waterloo Station (as Jeans puts it), whilst over the entire model the average would be more like one speck of dust for every 80 miles. Now returning to the distant nebulæ in this model, the strange behaviour referred to above is this: they all seem to be scattering away from us in a most unaccountable way, at speeds which are excessive compared to the speeds of most other astronomical bodies. The velocities of recession are something like 1,000 miles a second, and in one case even 2,350 miles a second. But perhaps it is well to say they *seem* to be moving away, because the only means we have of determining their motion and direction is the Doppler effect (p. 323), which is the displacement (in this case to the red) of the spectral lines.

Now de Sitter holds that the effect is apparent, and not real; he has, in fact, formulated a system of cosmology which differs from that of Einstein's relativity in one important

particular. Whilst Einstein's relativity considers the space-time continuum as independent of matter and postulates a definite distortion of this continuum by matter (so causing the effects of gravitation, bending of light, etc.), de Sitter supposes that the size of the Cosmos is determined by the amount of matter in it, and that space has adjusted itself to a particular size, suited to the amount of matter contained in it. Moreover, Einstein supposes space and time to be mathematically inseparable for anyone dealing with a limited fraction of the universe, but to become distinct for anyone who has the whole of space at his disposal, whereas de Sitter maintains "an equal partnership of space and time for the whole Cosmos." And on this theory, into which we cannot enter here, he holds (to quote Jeans) that "the stream of time rolls more rapidly just where we happen to be than anywhere else"; and so he is able to predict that the displacements, to the red of the spectral lines, are mere distance-effects and not true motion-effects at all.

This enables us to calculate the radius of the universe, which comes out at 2,000 million light-years, if the spectral displacements are proportional to distance. But they are not so proportional; in fact, there is a good deal of irregularity, and some of the nearer nebulæ are *approaching* us at about 200 miles a second. The fact seems to be that the distance-effect of de Sitter is superimposed on real intrinsic velocities and the two effects cannot be disentangled; but if certain assumptions are made of a statistical type, concerning random velocities it is possible to calculate on the basis of both effects, and then the radius of the universe comes out at only 80 million light-years.

It is impossible at present to know how much credence to attach to this last figure, but if it were true it would only be about half the distance of the farthest nebula which has been observed. In that case we are brought back to the idea that perhaps already we have penetrated beyond the confines of the universe, and are looking at what appear to be more distant objects, by a back view of the light from nearer objects, such light having travelled the long way round. According to

de Sitter, if there were no matter at all, light would take an infinite time to go round, but in the presence of matter its speed has a finite value; also his theory demands a non-constant velocity of matter itself, mere motion, in fact, changing its speed in a manner which ultimately depends on the radius of the universe.

Altogether the problem is too baffling to find any solution as yet, or even comprehension. We have various estimates, by various investigators, of the size of the universe, lying between the extremes of a radius of 80 million light-years (de Sitter) and 84,000 million (Hubble), and between these extremes it is at present impossible to decide.

In any case it is probably meaningless to imagine space and time by themselves, apart from matter, which occupies the continuum, however sparsely it may be distributed. Anyway, physical science is not only tending to this view, but is giving up trying to "explain" the multitudinous phenomena of Nature; physicists are more and more getting away from the old idea that an explanatory cause must be found for everything, and more and more resting content with describing phenomena in terms of mathematical expressions which fit the facts more or less faultlessly. The tendency now, for instance, is to leave *ether* out of their explanations, simply because they can get on better without it. But this does not necessarily mean that it is not there; it more likely means that the ultimate realities of Nature are never reached, because they may be beyond comprehension by the human intellect.

§ iii. Modern Geology

Regarding the earth from the broadest possible point of view, we cannot fail to note that its materials are arranged in three distinct layers—air, water and rock, sometimes called the atmosphere, hydrosphere and lithosphere. As we all know, the water, whether it be fresh or salt, is by no means uniformly distributed, but occurs in areas of every possible extent, from great oceans like the Pacific to mountain tarns. Next comes the land, similarly broken up into continents and islands, but

differing vastly from the water in being very heterogeneous. The question arises, What lies below the land areas and the oceans? If we take the density of water as unity, then experiment has shown that the average density of the rock-forming materials is about 2·7. Is the underlying substance denser still? We should expect it to be so, and we have abundant evidence to prove that our supposition is correct.

The Composition of the Earth's Crust.—An examination of the land surface to which we have access reveals to us that the crust is, in part, formed of stratified materials that have been laid down under water in far past ages, and of unstratified rocks that have had an entirely different (igneous) origin, and which may be collectively called granitic and basaltic. Granitic rocks (for which Suess proposed the generic name Sial) have a density of about 2·7, whilst basaltic rocks (Sima) reach an average of about 3·0. Over considerable areas of the land surface this heavier rock (basalt) is spread, and there is evidence to show that, in ages long past, and over and over again, it must have welled up (molten) to the surface and spread out in great sheets, through cracks in the crust from reservoirs below. Once exposed it was, of course, subject to denudation, and much of it, therefore, has been washed away, but what is left covers hundreds of thousands of square miles. There is also good reason to believe that the bed of the ocean is largely formed of basaltic rock, for oceanic islands, such as the Azores, that have never been connected with continents, are in the main composed of basalt. The fact that these basaltic rocks or lavas are very uniform in composition points to a common origin—*i.e.*, from what might be regarded as a deep-lying reservoir beneath the stratified layers.

So much, in brief, for the earth's crust. What is beneath this crust? Geologists consider that below the basalt there are heavier rocks consisting largely of iron magnesium silicate (peridotite or Femi of density 3·3) and, deeper, perhaps a thick layer of heavy oxides and sulphides (density over 5), surrounding the central core of nickel-iron (Nife) of density 8·2.

The actual density of this metallic core, whose radius is about half that of the earth, is calculated to be 12, and this

higher figure is due to the great pressure of the superincumbent layers. These views as to the constitution of the earth are mainly derived from a consideration of the mode and rate of propagation of earthquake waves (seismology). Very little is known of interior temperatures (see p. 352), which must be high, though not high enough to bring about a molten condition (except probably the iron core) owing to the high pressures prevailing. This internal heat is probably mainly due to the earth not having completely cooled down from its original state of incandescence, but, as we shall see (p. 356), it is partly derived from small quantities of radioactive elements present in the igneous crust.

To summarise, we may say that this crust is about 20 miles thick, solid, and consisting of say 6 miles of sial above and 14 miles of sima below; beneath this is the vast rigid mass of femi, oxides and sulphides, sometimes known as the Dunite shell, about 1,800 miles thick, leaving a core principally iron, which may be molten, whose radius would be about 2,000 miles.

The Foundations of Modern Geology.—Modern geology is not much more than fifty years old, and regards earth structure from a point of view that did not present itself to the geologists of last century. We are fortunate in possessing authoritative statements on the subject by a distinguished geologist, Professor Joly of Trinity College, Dublin, of which we shall avail ourselves fully in the following pages. In a recent letter to the author, Professor Joly wrote: "The main factors have been revolutions, or periods of mountain building, isostasy and radioactivity. All modern geology rests on these foundations." We cannot, therefore, do better than attempt, however imperfectly, to understand what these "foundations" are.

There are one or two general features in the configuration of the earth's surface that must be noted before passing to details. These features may be readily appreciated with the aid of a good physical atlas, but Fig. 106 will give us the essentials.

The first point to note is that the land areas are orientated north and south, being separated by the great oceans which stretch from pole to pole, both of which latter are themselves

seagirt. Secondly, the general trend of the mountain ranges is also north to south, save in the case of the Eurasian mountains, where it is east to west. Thirdly, "the greatest mountains confront the widest oceans," and run more or less parallel with the coast-line, even the (geologically speaking) recently formed Himalayas facing the Indian Ocean. The general conclusion is that there must be an intimate connection between orogenesis, or mountain-building, and the ocean expanses, that,

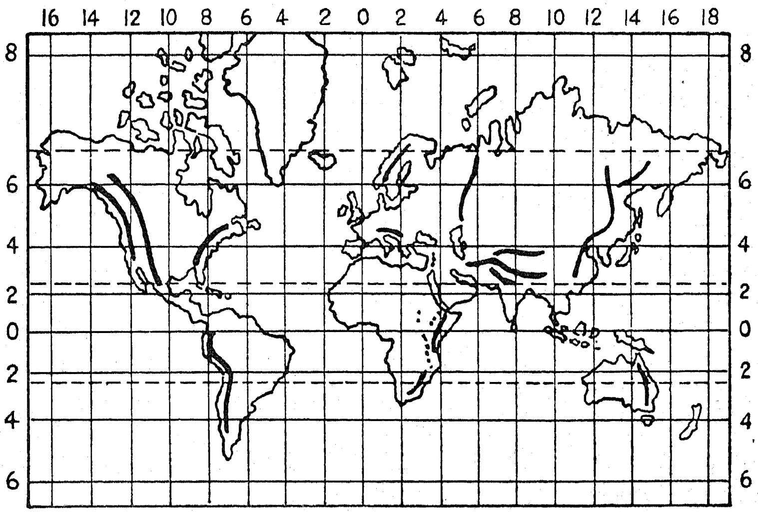


FIG. 106.—DISTRIBUTION OF MOUNTAIN RANGES: THE AFRICAN RIFT.

in short, "most of the great mountain ranges of the globe have been formed by thrusts from the nearest ocean basin" (Ransome).

Another prominent feature of the earth's surface is the existence of cracks or rifts stretching north and south, such as the African Rift Valley (Fig. 106, dotted line), occupied now by the double chain of the great lakes, and, forking in the north, eastwardly as the Gulf of Aden and westwards as the Red Sea, continued as the Valley of the Jordan. Similar rifts on a smaller scale occur in other quarters of the globe, and all are due to tensional forces at right angles to their general trends.

"He who has visited any of the great mountain regions of

the earth is impressed by the greatness of the forces which must have prevailed. He judges the greatness of the forces by that 'strength of the hills' which they have overcome. He will also reflect upon the operation of other forces—forces of the feeblest description—slow and silent in operation. And here he comes to see that not less influential than those overwhelming forces which have uplifted the mountains is the time-element which integrates the feeble forces of friction and solution over geological areas. The one uplifts; the other pulls down. In the history of the earth, mountain ranges have come and gone; come and gone many times. The great forces uplifting; the feeble ones, aided by inexhaustible time, pulling down."

"But there is obviously a mystery underlying the whole matter. Whence come the great constructive forces which to-day seem to be as great as they were in the most remote past? They have not grown weary at their work; for the existing mountain ranges—of recent date as we shall see—are equal to, if they do not exceed, those of former ages."

"The mystery deepens when we are told that these great folding forces proceed from the ocean, and that their magnitudes are measured by the ocean-span."

"We find also that crushing is not the only form of stress which has racked the continents. Irresistible tensions have also prevailed in the past, and we have presented to us the spectacle of one of the greatest of the continents rent from end to end by these tensile forces. We ask in turn whence come these tensional forces?"

"But these facts do not exhaust the element of mystery prevailing over the surface features of the earth. Our cities are raised on rocks which formerly were far beneath the surface of the ocean. Right across the great continents stretch the floors of ancient seas. And geological research tells us that not for the first time have these continental regions risen from the ocean to receive the light of the sun. There were repeated submergences and repeated resurrections."

"Finally, and most remarkable of all, an orderly sequence has prevailed in these great events; the entire surface-history of the earth being, as it were, laid out according to a succession

of these events, sundered by enormous intervals of geological time. The phenomena of the resurrection of the land and of the mountains are physically connected—spring from a common source—and in due course both land and mountain range find a common grave in the ocean waters rising over the continents" (Joly, "Surface History of the Earth").

We have become so accustomed in our brief span of life to look on the majesty of the "eternal hills" and to ignore the erosion of their flanks and summits that has gone on unceasingly for countless centuries; to think of the oceans as vast quiescent expanses of water, ruffled, it may be, from day to day, by local storms, and to neglect the great forces ever active beneath their beds and under the land that rears its shoulders above the waters, that reflections such as those we have quoted must come to us almost as a revelation. Geologists in the past merely scratched the surface of the earth; geologists of today seek to know the greater things that underlie these surface scratchings, and to probe the mysterious forces that made the earth what it is.

The Estimation of the Density of the Earth.—As long ago as 1774 Maskelyne, the Astronomer Royal of those days, made the first attempt at determining the density of the earth. He based his work on a statement made by Newton that a plumb-line suspended near a mountain, whose weight and size were known, would be attracted to the mountain, and that, if the amount of that attraction were compared with the attraction of the earth as a whole, the density of the globe could be deduced. Newton made the remarkably accurate guess that that density was about five and a half times that of water.

Maskelyne made his experiment on an isolated, conical hill in Perthshire, called Schehallion, which reaches a height of 3,547 feet. The volume of the mountain having been determined by survey and its density computed from that of its constituent rocks, the deviation of the plumbline on opposite sides of the mountain was calculated and found to be EFD (Fig. 107), which gave the difference between the pull of the whole earth and the pull of Schehallion. These experiments were repeated by Hutton and also by others on Arthur's Seat near Edinburgh,

and on the great extinct volcano in Ecuador, Chimborazo, which is 20,498 feet high. The result of all these measurements was to show that the globe as a whole was about five times as dense as water. Since, as we have seen, the surface rocks vary in density from 2·7 to 3, it followed that the materials forming the mass of the earth must be much denser than these (see p. 343).

Another method of tackling the question was that adopted in 1854 by Sir George Airy—viz., by means of the pendulum—but estimates made in this way were found to be unreliable.

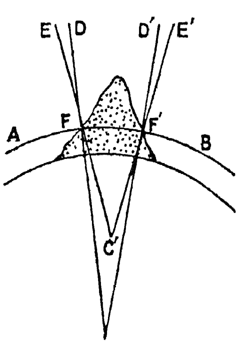


FIG. 107.—MASKELYNE'S EXPERIMENT.

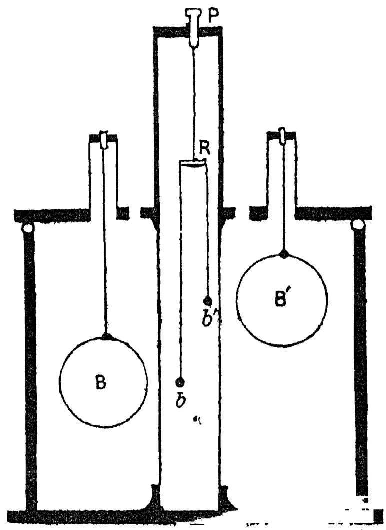


FIG. 108.—BOYS'S EXPERIMENT.

Finally, a more accurate method was employed, based on that used by Cavendish in the end of the eighteenth century. Cavendish's apparatus was vastly improved by Professor Vernon Boys of Oxford, and used by him during the years 1895-1900. The general plan of the apparatus may be understood from Fig. 108. Two small gold balls, *b* and *b′*, each $\frac{1}{5}$ inch in diameter, are suspended by very fine quartz fibres from the end of a rod, R, which carries a small mirror. R is in turn suspended by a quartz fibre from the pin P. B and B′ are two lead balls, each $4\frac{1}{2}$ inches in diameter, and capable of being

twisted round so that B may hang behind *b*, and B′ in front of *b*′. B and B′ attract *b* and *b*′, and the twist or torsion of the fibre carrying the rod R can be measured by the reflection from the mirror on a graduated scale. The whole apparatus is enclosed in an airtight chamber, and vibration eliminated as far as possible by conducting the experiments in the crypt of an Oxford college. It was found that the pull of the lead balls on the gold ones, against the earth's attraction, could be estimated even when it amounted only to one-millionth of a gramme. From numerous observations it was calculated that the density of the earth was 5·5268 times that of water, so that Newton's guess was almost exactly correct.

Periodic Movements of the Earth's Crust.—It is rather startling to be told that the land level is in almost constant movement, not merely movements of a seismic nature, of which we immediately think when the statement is made. When a high tide climbs the shore millions on millions of tons of water are added to the weight borne by the coast-line, and it is estimated that the West Coast of Ireland sinks about 3 inches at every high tide, to rise again at ebb, when the superincumbent load of water is withdrawn. When 1 inch of rain falls on a square mile of continental area, it adds a weight equal to 60,000 tons, but although this will induce a sinking of the land, the depression is not permanent, for the original level is restored when the water evaporates or drains away. But if a river deposits silt or mud the deposit is permanent, and the gradually increasing weight causes a lowering of the land level, balanced, however, by the continual deposition of more material. Hence it is quite possible for stratified rocks to be as much as 3,000 or 4,000 feet thick, and yet to have been laid down in comparatively shallow water, the depression of the land keeping pace with the added layers of sediment. Conversely, continual denudation, scraping and washing off the land surface, therefore lessening the weight borne by the crust, may lead to a slow elevation, so that the surface remains at an approximately constant height. The different parts of the earth are thus to be regarded as in a state of isostatic equilibrium.

Isostasy.—The term "isostasy," as applied to the earth's crust, may be briefly explained by saying that if we imagine a gigantic cheese-borer capable of scooping out a pillar of solid material from the surface inwards to a common distance from the centre, the pillars, if of the same diameter, would be approximately of the same weight, but not of the same height, for the continents stand higher than the beds of the ocean, and the materials of which they are composed are of lower density.

This question made itself rather prominent during a survey of India taken about the middle of last century. The survey and the plumbline did not give the same results at certain stations south of the Himalayas, and it was thought that the attraction of the great "massif" to the north was the cause of the discrepancy. The geologist, Pratt, calculated what this attraction should amount to, assuming the density of the mountains as 2·75, and found it to be three times as much as it actually was observed to be. Why did the mountains not pull the plumbline more than they did? Sir George Airy put forward a suggestion which has been universally accepted—viz., that just as an iceberg standing 300 feet above water-level may have a depth of 2,400 feet below water, so a lofty range of mountains sends down a considerable portion of itself into the substratum. The mountains, owing to their great height, certainly do exert a plumbline attraction above, but this will tend to be equalised by a diminished attraction below, owing to the substitution of lighter materials for the heavier lava. The theory of isostasy "involves the view that the lighter continental crust floats upon a universal substratum of heavier materials." Indeed, the parallel with the iceberg is fully upheld, for it has been found that "the emergent volume bears to the submerged volume approximately the ratio of 1: 8," which, as it happens, is that usually shown by a floating iceberg, 300: 2,400, as in the example just given.

About 1920, Wegener put forward the hypothesis that the continents themselves are not fixed, but in a condition of slow drift, as masses of the sial, floating upon a hypothetical magma beneath, become detached owing to tidal or other strain. In this way, for instance, the American continent in past

ages has slowly drifted apart from Europe and Africa in a westward direction, and this view is certainly confirmed by fossil similarities in the rock strata on each side of the Atlantic, and by some correspondence in the shape of the shore lines. As yet, however, it is impossible to test the truth of this ingenious hypothesis, and meantime it must be admitted that seismological evidence indicates that the rocks beneath the crust are very rigid.

Those who have made a life-study of earthquakes tell us that the movements are in the form of waves, faster ones, termed "preliminary tremors," gradually becoming longer and slower; and they also tell us that the separation of these two kinds of waves can take place only in a homogeneous medium, for a heterogeneous medium would result in a regular jumble of waves. Working out the matter theoretically, Knott showed that these waves must travel below the continental masses, and he estimated that the homogeneous rocks through which they pass extend about twenty miles below the surface; and this estimate is confirmed by other evidence, which we need not consider. Further, we may note that the seismic waves travel along the ocean bed in general more rapidly than below a continent; a point in support of the view that the floor of the ocean is largely basaltic in its nature. The Sima basis even if plastic behaves as a rigid, elastic, highly heated solid (sometimes known as the Diorite or Tachylite layer) and, below this layer, the vastly thicker Dunite shell (p. 344) is also solid.

Radioactivity of the Rocks.—All the rocks composing the earth's crust, including the extruded basalts, contain traces of radioactive elements that are continually changing into elements of lower atomic weight and giving out heat in the process. The parent radioactive elements are uranium and thorium, and these, as they disintegrate, degenerate finally into the common metal lead. The disintegration is extremely slow, for it has been estimated that half of the uranium now upon the earth will have disappeared in about 5,000 million years, and one-half of the thorium in about 13,000 million years! Now since the oldest sedimentary rocks were deposited in the primeval oceans not less but probably

far more than 200 million years ago, "geological time is but a small fraction of the period it will take to reduce sensibly the influence of radioactivity." Potassium is also radioactive, though very feebly so, but as it occurs in considerable amounts in many rock-forming minerals it must, as a source of heat, be taken into account (Holmes and Lawson). It is quite impossible for us to go into the calculations that have been made as to the amount of heat that escapes to the surface of the earth from its interior; all that we can do is to give the result —viz., that the average temperature at the base of the continents is about 960° C.—*i.e.*, rather below the melting-point of basalt. The deduction from the data that have been accumulated is that the substratum must be storing its own radioactive heat. "It cannot be passing upwards to the terrestrial surface, for the continental radioactive heat accounts for almost all that is escaping at the surface." What becomes of it we shall see presently (p. 356).

What is the condition of affairs under the oceans? The ocean bed is, as we have seen, in all probability for the greater part basaltic in its nature, and any radioactive heat developed in its surface layers must pass by conductivity into the overlying waters; but in the deeper layers a level must be reached where conservation of heat must take place, and whence it cannot escape, since the upper crust will act in the same way as the continental rocks do over the substratum on land. It has been estimated that this conservation of heat occurs at a depth of about thirty miles. What the radioactive conditions are in the layers below we have no means of knowing; but there appears to be a diminution in the amount of radioactive heat in the very deep layers.

The Age of the Earth.—The age of the earth has always been a fascinating question. The Chaldean astronomers thought the earth was born about two million years ago, but most of the ancient cosmogonists made the genesis of the earth coincident with that of man. The Irish Archbishop Usher, in the middle of the seventeenth century, held that the creation of the world took place 4,004 years B.C., a fanciful date recorded in some Bibles at the present day. At the other extreme we

have the views of the Brahmins who held that the earth was eternal. After the birth of geology as a science at the end of the eighteenth century, various attempts were made to solve the problem, more especially by estimating the time that it must have taken to deposit the vast series of stratified rocks, calculated to be at least 500,000 feet thick when piled one on the top of the other. The evolution of organic life also demanded a prodigious number of years, and geologists and biologists alike were naturally at loggerheads with physicists, like Lord Kelvin, who said that not more than 40 million years had elapsed since the earth was a molten globe. The discovery of radioactive bodies in the beginning of this century showed that Kelvin's estimate was hopelessly wrong.

Another method of estimating the age of the earth was proposed by Joly in 1899, based on calculations of the amount of sodium in the oceans and the amount added per annum. After many observations made in all parts of the world the figures worked out to 12,600 million million tons of sodium in the oceans as against 156 million tons added year by year. This would give about 81 million years as the age of the ocean, but many authorities regard the figure representing the annual increment as far too high, and consider that 35 million is nearer the truth. If that be so, we should get 330 million years as the age of the oceans; but even that number is considered by Professor Gregory as far too small. In 1921 he told the British Association that "multiplication by five would not be excessive."

During the past few years, as we have said, an entirely new method of estimating the age of the earth has been put forward, based on the rate of disintegration of the radioactive elements, uranium and thorium. It is known that an atom of uranium generates ultimately eight atoms of helium and one atom of lead, while one of thorium gives six atoms of helium and one of lead. The atomic weight of uranium, which is greater than that of any other element known, is 238·1, and thorium has an atomic weight of 232·1; but both degenerate into forms of metallic lead which have not the same atomic weights as ordinary lead. Uranium-lead has an atomic weight of 206, thorium-lead 208, while that of ordinary lead, which is a mixture of the two, is 207·2.

These varieties of lead are of course "isotopes" (p. 256), and though they possess the same chemical properties, they may yet be physically distinguished from each other. Now it has been found that a million grammes of uranium give rise to $\frac{1}{7600}$ of a gram of lead per year, and the same amount of thorium to $\frac{1}{19500}$ of a gramme of lead in the same time. Lord Rayleigh, in 1921, said that the rate of disintegration of uranium could be "relied upon to have been the same in the past as we now observe it to be." If we calculate the amount of lead present in any uranium-bearing mineral we have a datum on which to base an estimate of the length of time it has taken to produce it. From such data Rutherford has calculated that the age of the earth is not less than 3,000 million years, and possibly may be rather more. Anthropologists and geologists agree in saying that man existed on the earth 300,000 years ago, so that humanity is now little more than in its babyhood. As Dr. (now Sir) J. A. Jeans puts it (*Nature*, March, 1928): "He is still concerned with his cradle and his feeding-bottle, and is just beginning to look with questioning eyes on the universe into which he has been born." Like the "three little maids" in the "Mikado," he is wondering "what on earth the world can be."

Periodicity in the Revolutions.—A general survey of the earth's surface reveals what, at first sight, appears nothing but a confused jumble of more or less stratified rocks, tilted upon end, twisted, contorted and folded over each other, layer after layer; and, underlying them, great masses of unstratified materials whose origin must have been entirely different from the stratified types, which had manifestly been laid down in the sea. It was this confused jumble that geologists of the nineteenth century, like Smith, Murchison and Sedgwick, set themselves to unravel, with such success that they were able at last to present us with an orderly sequence of the surface layers of the earth's crust, such as that given on p. 101.

Later on, it became apparent that all the great mountain ranges—Andes, Rockies, Himalayas—and the lesser ones—Alps, Caucasus, Carpathians, Urals—were of comparatively recent origin, and carried on their flanks stratified rocks very much older than themselves. Moreover, it transpired that these

mountain ranges had all been formed about the same time in a geological sense. Further, denudation had entirely changed the aspect of the mountains since they were first formed. The overlying strata had been stripped off and the roots exposed, revealing the existence in far past eons of yet earlier mountain ranges, whose worn-down stumps alone persist. The general conclusion forced upon us by the study of such facts is that the surface of the earth has passed through a succession of alternating phases of comparative quiescence and tremendous disturbance. First, the continents began to sink very, very slowly, and the ocean began to encroach on the land, pushing forward and retreating alternately, just as rippling wavelets creep up a low-lying shore, one wave reaching a level not attained by the next, but overpassed by a third. At length the high tide mark is reached and the reverse movements begin, retreat exceeding advance, and the land emerges once more. The next stage is the elevation of the mountain ranges. All the consolidated deposits, formed in the period when the seas covered the land, are heaved up by some huge subaquatic thrust from the ocean, acting approximately at right angles to the orientation of the uplifted ridges, crushing and folding them into all sorts of irregular shapes, and altering the levels they exhibited when they were laid down horizontally in the sea. So came an uplift from below, hoisting the ridges into mountain ranges, often thousands of feet above the level of the mass of the new continents. Then followed a quiescent period while the forces of denudation carried out their silent labours, carving out valleys and sculpturing the peaks into the forms they ultimately assumed, until after, it might have been, millions of years, the continents slowly sank and the whole cycle of oceanic invasion, silt deposition, retreat and upheaval began once more.

There is abundant evidence to show that there have been several of these mighty "revolutions," as the American geologists call them, in the history of the earth, following each other at intervals of many millions of years; and the times of their occurrence have been determined in relation to the order of succession of the rocks as made out by the geologists of last century. The last great upheaval took place in tertiary times,

when all the well-known mountain ranges that figure in our atlases were formed, and we are now living in the quiescent period following that upheaval, the period of slow sinkage of continental levels, and witnessing the denudation of the lofty peaks and elevated plateaux that came into being long ages before man or even his anthropoid ancestors appeared on the earth.

Causes of the Revolutions.—Finally, we have to ask ourselves, what brought these revolutions about? We have already seen that both the continental areas and the oceans rest on a basaltic substratum which is at present solid; that the continental rocks and those underlying them are feebly radioactive; and that although heat is continually being produced it is not lost to any great extent, but is, on the contrary, accumulating.

PERIOD	SYSTEM	REVOLUTION
	Recent	
	Pleistocene	
	Pliocene	
Tertiary	Miocene	
	Oligocene	Alpine
	Eocene	
	Cretaceous	Laramide
Secondary	Jurassic	
	Triassic	
	Permian	Appalachian
	Carboniferous	
Primary	Devonian	
	Silurian	Caledonian
	Ordovician	
	Cambrian	Laurentian
Archæan	Precambrian	

FIG. 109.—THE REVOLUTIONS.

The substratum, it was pointed out, was nearing its melting temperature, viz. 960° C. as against 1,150° C. This difference and the latent heat of melting has yet to be supplied, and, from experimental data, Joly concludes that "about 33 million years must elapse in order that the requisite heat may accumulate and fusion be brought about." When the solid substratum liquefies and the land support is therefore withdrawn, the continents must slowly sink relative to the ocean level, permitting the waters to spread over the lower reaches of the land. "The solid crust of the earth, consisting of the continents and ocean floor, is being stressed by the increasing volume of the substratum. The earth is, in fact, increasing in volume, and its solid crust is too small to fit a larger world. Two effects inevitably follow—fluid pressure in the substratum and corresponding tensile stress in the crust."

When the fusion (melting) beccmes general the whole crust

of the earth is raised up, and when solidification follows and the interior contracts, the covering has to accommodate itself accordingly, and so the rocks become compressed, folded, and elevated into ridges, just as the skin of an apple wrinkles as the contents contract.

The world has thus, during all geological time, been pulsating rhythmically in accordance with the accumulation and dissipation of the heat of the basaltic basis, "fusion and expansion being followed in every cycle by consolidation and contraction" (Holmes); and this alternation of thermal conditions depends in turn on the radioactivity of the rocks.

"We can best realise what that trace of radioactivity means to the life upon the earth by looking forward to a day when it will at length be worn out. Mountains, unrejuvenated, must then sink down into the plains. Continents worn away age after age by sea and sky must be washed irrevocably into the ocean. Air-breathing life upon the land and land vegetation must finally perish. For the earth itself will have ceased to breathe. And the mind of man, which alone comprehends it all, will have become part of the forgotten past" (Joly).

But there are other factors of an astronomical kind, also to be reckoned with in considering the future of the earth. The small tidal influence which the sun is constantly exerting on the earth has the effect of making the latter, as well as the other planets, rotate more slowly, and recede from the sun; also the much greater tidal influence due to the moon will, according to Jeffreys, lengthen out the day, till after 50,000 million years it will be equal to forty-seven of our present days, and the moon will then have receded to its farthest distance from the earth before it begins to approach again (see p. 337). After a million million years the sun will radiate sensibly less heat than it does now, even if it has not before then passed over into an insignificant dwarf (see p. 311), so that from all these causes the mean temperature of the earth will drop by a matter of 30° C. or so, sufficient to freeze the oceans and rule out the possibility of life as we know it now. Moreover, accidents may happen such as another wandering star coming so close as to deflect the earth's course round the sun, or even collide

with it; or an asteroid might collide with the earth. Such things are remotely possible, but in the last degree likely, so that though the outlook is bleak, so far as the very distant future is concerned, it is probable that no great changes will occur in the next few millions of years.

Ice-ages.—The most likely changes in this relatively short period ahead are those slowly recurrent oscillations of mean temperature that have led to ice-ages in the past. We have already dealt with (pp. 103-105) the last great ice-age, but it is now recognised that earlier ice-ages have existed with inter-glacial periods in between, though it is not known how often the process has been repeated in the past.

A simple explanation of these recurrent ice-ages has been given by G. C. Simpson, viz. polar shift and variation in solar radiation, to the extent of 20 per cent. or more, over periods of about 250,000 years between maxima. There is nothing improbable in the assumption that the sun is a slightly variable star of long period, for it is known to be so over the short period of eleven years associated with sun-spot activity. When the sun-spots are at a maximum the radiative energy of the sun is slightly greater than when they are at minimum, and this increased radiation falling on the earth causes a slight rise in the mean temperature. But there is a relatively greater increase at the equator than at the poles, and the result of this increased *difference* in temperature is (1) more activity in the general circulation of the atmosphere (see p. 368) and (2) greater evaporation from the equatorial oceans causing increased cloud and precipitation of rain. It is true that the climate of England is not appreciably affected by the eleven-year cycle because, being near the cyclonic track, the effects are swamped by other more or less accidental effects; but, speaking broadly, the rainfall of the world is at a maximum when sun-spots are at a maximum—*i.e.*, every eleven years.

When we come to consider the greater amplitude of solar variation in the long periods of about 250,000 years, it is easy to see that there will be maxima in the precipitation of rain and snow, corresponding to the maxima of solar radiation. It is during the long time when the precipitation of snow is

steadily increasing towards a maximum, in those regions where the mean temperature is about 0° C., that the ice-age sets in, for the snow is increasing constantly, while the solar radiation is as yet not powerful enough to melt it; and so the ice-caps surrounding the polar areas extend towards the equator, while those surrounding high mountains and tablelands extend to the lowlands. When later the sun reaches maximum activity, the increased heat now melts away all the accumulated glaciers, and the increased precipitation takes the form of rain; but a time eventually comes when the declining radiation once more reduces the temperature of these regions, causing snow to appear; and so another ice-age supervenes.

If we now follow the course of events, the position becomes interesting. As the solar radiation goes on declining precipitation virtually ceases in the regions we are considering, there is less cloud and so more sunshine, which though it is weaker than when at maximum gradually melts away the snow; a long relatively calm and serene period follows, a dry interglacial period perhaps five times as long as the wet one mentioned above, during which the solar radiation is all the while steadily falling to a minimum, then later slowly rising again to a maximum, when the cycle of changes outlined above commences over again.

On this ingenious theory of Simpson one complete cycle involves the following sequence:

1. Ice-age with increasing solar radiation.
2. Short wet interglacial period at maximum radiation.
3. Ice-age with decreasing radiation.
4. Long dry interglacial period, on each side of the point of minimum radiation.

At the present time the world appears to be somewhere about the middle of period (4), and if so we may expect another glacial epoch to begin in about 80,000 years.

The Earth's Atmosphere.—A word should be said first about planetary atmospheres, as these help us the better to understand the case of the earth. Unusual interest attaches itself to the nature of the atmospheres surrounding the planets,

inasmuch as the possibility of extra-terrestrial life is involved, but it is surprising how little really is known. The telescope affords relatively little information, but the spectroscope is of value in revealing the fact that the light observed is merely that of the sun, reflected by the atmospheres or solid surfaces of the planets, with some special absorption lines, due to the atmospheres themselves. The planets therefore do not shine by their own light, and so must be relatively cool, on the surface at any rate. The radiometer (p. 321), moreover, has enabled the surface temperatures to be determined, and particularly the variation of temperature on Mars with respect to latitude, season, and the hour of day. These temperatures have already been referred to (p. 314), and from the observations in general useful conclusions have been drawn—for example, that Mercury always faces the sun on the same side (like the moon with respect to the earth), and that this side has a scorching heat which would more than melt lead, while the other side is excessively cold; it has no atmosphere. The other extreme is found in the distant planets, Jupiter and Saturn, for example, showing a surface temperature of about $-173°$ C. These latter temperatures are very approximately those calculated for rapidly rotating black-body spheres, taking into account that the amount of radiation absorbed per unit area falls off as the inverse square of the distance from the sun—calculations which show that Jupiter should have a surface temperature of $-152°$ C. and Saturn $-183°$ C. As these giant planets are by no means black, but have what is called a high "albedo" or reflecting power, which would involve loss of some 60 per cent. of the radiant energy, it may be concluded that the observed temperatures are somewhat in excess of what would be expected from the sun's heat alone—that is, these planets are warm, and indeed may be very hot within.

A theoretical method of approach, involving the kinetic theory (p. 224), enables us to form better pictures of the probable facts than observational methods. It has already been shown (p. 337) that in all probability the planets were born out of the incandescent gaseous matter forming the surface of the sun, matter containing practically all the elements, but some like

hydrogen, oxygen, silicon, calcium, and iron in greatest abundance. When this gaseous matter settled down into globes, more or less liquefied by cooling, the still gaseous envelopes or atmospheres must have undergone considerable changes during the long process of cooling down. These changes can be easily visualised in the case of the earth, of which we know most, but the picture we are now going to draw (pp. 361-365) is of course essentially speculative. The heavier elements (principally iron) must have first settled to the centre, followed by calcium and silicon compounds, etc., floating as a sort of siliceous slag on top, with an incandescent, greatly swollen atmospheric envelope consisting of the lighter elements. As the latter cooled in the outer regions combination of these elements, to form compounds, must have occurred, the heavier compounds eventually gravitating to the liquid core beneath. Finally, a hot atmosphere consisting principally of steam and carbon dioxide must have remained, but probably much of the lighter portion of the hot atmosphere escaped into space during this long process of cooling.

Primeval Earth's Atmosphere.—It must be remembered that the mean velocity of molecules is greater the lighter they are and the higher the temperature (see p. 224). At the earth's surface if there were any exceeding seven miles a second they would gradually escape; but with an inflated atmosphere a proportion of these molecules would be so far from the earth's centre of gravity that the critical speed for escape would be even less than seven miles a second, since the gravitational potential falls off with the square of the distance from the centre. It is probable that a good deal of hydrogen was lost in this way, and it is certain that if the earth had been less massive it would have lost a good deal more of its substance than it has done. The kinetic theory enables us to say what gases would be lost for any planet, given the mass of the planet, the temperature and distance (from the centre of gravity) of the molecules of the gas. The planet Mercury, for instance, is now too hot and too small to retain any atmosphere, and Mars has lost, in all probability, an enormous amount of its lighter materials, whilst the moon, although of much the same mean temperature

now as the earth is, cannot retain any atmosphere because its gravitational potential is too small.

There must have come a time in the history of the earth when the liquid or solid globe was still red-hot and the steam atmosphere weighed some two or three hundred times at least what the present atmosphere does. The original carbon dioxide had by now largely entered into combination with mineral components of the surface forming carbonates; there was, presumably, a small percentage of nitrogen in this hot atmosphere, though probably no oxygen, as this chemically active element would more likely have entered into combination with mineral components of the solidifying crust. High up above this steam atmosphere we may picture a vast canopy of clouds of enormous thickness, reflecting from their upper and outer surfaces the bright sunshine, none of which could penetrate through, and precipitating beneath deluges of condensed water with appalling discharges of lightning and thunder. This precipitated water could only exist within a limited upper region of temperature and pressure, and in the lower, hotter strata, above the critical temperature (365° C.), the liquid would change to the gaseous condition. At the surface itself, owing to the pressure of say 200 atmospheres, the density of the steam must have approximated to that of water itself (say one-fifth), and at this temperature and concentration water is a very reactive chemical substance, almost acidic in its properties; so that enormous solution in, and hydrolytic decomposition of, the crystallising rocks beneath must have occurred.

The above picture may represent what is happening on Jupiter at the present day; owing to its vast size it would presumably not have reached the stage of cooling which the earth has reached today, and it is certain from telescopic observations that the atmosphere of Jupiter is in a condition of most stupendous turmoil. The surface we see may actually be hundreds if not thousands of miles above the hot liquid or semi-solid core beneath, and the temperature (−173° C.) observed is not necessarily inconsistent with such a condition of things, since by adiabatic cooling (see p. 366) there would

be an enormous difference between the temperature of the core and that of the upper atmosphere. The visible surface of Jupiter and Saturn, on this view, represents the tops of clouds (which may or may not be water) of enormous thickness; and the more rapid rotation of the equatorial regions as compared with those of higher latitude may be due, as in the case of the sun, to the shape of the core itself being equatorially elongated rather than spherical, owing to a speed of rotation very much greater than the observed ten hours or so for the surface of gaseous envelope.

Returning to our imaginary history of the earth's atmosphere, a time came when the cooling was sufficient to bring the lower strata to the critical temperature, and when this happened the highly compressed steam beneath gradually contracted and gave birth to a boiling ocean whose temperature steadily fell from 365° C. to its present-day value. How long the entire cooling process took we cannot even guess, but it must have been presumably many million years, being, in fact, retarded by the dense steam clouds, above, serving to slow down the loss of heat by radiation. During the later period the pressure of the atmosphere was steadily diminishing as more and more steam became water; and eventually practically nothing remained except the original amount of nitrogen, with a little carbon dioxide and a minute proportion of the inert gases, all accompanied by a good deal of water vapour as moisture. The earth had now cooled down to say 50° C., a state which we may suppose is similar to Venus at the present day, the steamy atmosphere being surmounted by a thick canopy of clouds, through which the sunshine could only penetrate with difficulty. Venus, on this view, although it is practically the same size as the earth, has cooled down more slowly, because being nearer the sun it receives twice the amount of solar radiation (see p. 258); and the bright surface which we see consists of the cold tops of these clouds. The solid surface of the planet is never seen, but it is probably at a temperature of about 50° C., and spectroscopic observation has shown that oxygen is absent, or at any rate less than ·1 per cent. of the terrestrial amount in the region above the clouds. The reason for the difference in

temperature between surface and upper atmosphere will be dealt with presently.

Beginning of Life.—Returning once more to earth, we may presume that, somewhere about the period we are speaking of, with a warm ocean, chemical activity of all kinds must have been much greater than it is now, for in general chemical velocity more than doubles itself for each rise of 10° C.; and it is possible that, in the welter of chemical changes taking place, complex carbon compounds (organic substances) were produced, some of these of a colloid nature (see p. 407), functioning as activators of chemical change, or what we call catalysts (see p. 396), such as enzymes (p. 447) are. These catalysts would be the precursors of the lowest forms of life, which may have been similar to the so-called auto-trophic, bacteria—*viz.*, the nitrite- and nitrate-bacteria (see p. 419), whose life depends mainly on the chemical energy contained in inorganic compounds.

Other low bacteria (unicellular organisms, p. 419) have similar functions; thus sulphur-bacteria convert sulphides to sulphates, iron-bacteria convert ferrous compounds to ferric, while nitrite- and nitrate-bacteria convert ammonia into nitrates. In all these cases carbon dioxide is utilised somehow in building up protoplasm, the energy being derived by oxidation of the sulphide, ferrous compound, or ammonia respectively. These bacteria, therefore, require oxygen; but there are others, called anaerobic bacteria, which do not require oxygen but derive their energy from the chemical changes which they induce, and it is possible that the first living organisms which appeared derived their energy, not from oxidation by oxygen but from nitrites and nitrates, which must have abounded in the primeval ocean owing to violent thunderstorms (which are known to produce nitrous and nitric acids).

However this may be, certain it is that when the sun's rays were able to penetrate through the clouds a new group of complex organic compounds (chlorophyll group—see p. 438) became associated with the low forms of life, and a new epoch was ushered in. For it is the function of chlorophyll, under the influence of solar rays, to decompose carbon dioxide, liberating oxygen and building up synthetically the materials of living

protoplasm as we know it now. Oxygen now began to appear in the atmosphere and the new forms of life became to a large extent dependent on it, both plants and animals; and from this time onwards oxygen formed the most important constituent of the atmosphere. Its amount today (21 per cent. by volume of dry air) is maintained by the plant life of the earth, whilst the carbon dioxide (·04 per cent.), which is a product of respiration of both plants and animals, is maintained at this level mainly through its continual assimilation by plants and its solution in the waters covering the earth.

The other components of the atmosphere of today besides its principal one (nitrogen, 78 per cent. by volume of dry air) are hydrogen and the inert gases argon, helium, neon, krypton, and xenon (all in traces except argon, nearly 1 per cent.). Moisture, of course, is very variable (1 to 5 per cent.), dependent on humidity —*i.e.*, climate and weather. Of ozone (O_3—*i.e.*, a molecule of oxygen containing 3 atoms) there is none, except in the highest reaches of the stratosphere (p. 369), where probably also there is relatively more hydrogen and helium. These upper reaches are warm and partly ionised (see p. 255) by the intensity of solar radiation, and the ionisation is responsible for the Aurora Borealis, as well as the deflection of radio-waves by the so-called Heaviside layer, at about 30 miles height by day and about 60 miles at night. The pressure and density of the earth's atmosphere fall off rapidly with height, being only about a half of the surface value at about 17,000 feet (above the top of Mont Blanc); while at the average height of the troposphere (p. 369), or say 7 miles, the pressure is less than one-fourth of an atmosphere. But there is still a perceptible atmosphere at heights of hundreds of miles, and Jeans has calculated that even at 1,800 miles the density is such as to give 300,000 molecules to the cubic centimetre, but this is only one hundred million millionth of the number at the surface.

Meteorology.—The earth's atmosphere when dry and clear of clouds or smoke, etc., is very transparent to solar radiation, but the ozone of the upper regions cuts out radiation of the far ultra-violet below a wave-length of 2,885 Ångström units (p. 259), and in any case 37 per cent. of the total incident solar

radiation is lost in the upper regions by reflection and scattering (see p. 270). As it is the wave-lengths in the blue region of the visible solar spectrum which are most scattered, the sky appears blue.

The variable moisture content of the earth's atmosphere plays an enormous part in determining weather and climate. Even if there are no clouds this moisture, being much more opaque to infra-red radiation than oxygen and nitrogen, cuts off a lot of such radiation, but since it also cuts off relatively more (see p. 266) from the earth itself, moisture tends to conserve the earth's surface-heat by preventing excessive cooling at night. The formation of clouds is due entirely to adiabatic cooling of moist air by rising. It has already been pointed out under the kinetic theory (p. 226) that when air rises to a region of lower pressure and expands, it cools itself in so doing. The adiabatic laws controlling this important cooling process have been developed with great mathematical accuracy, and they enable us to calculate what the temperature fall will be for all conditions of temperature and pressure initially. Broadly speaking, the calculated fall, or so-called lapse-rate, is of the order of 10° C. per kilometre rise, near the surface for normal conditions. A kilometre is rather more than 3,000 feet, so if we could take up expanding *dry* air to this height and prevent any heat getting into it (from the sun or the earth by radiation) it would be 10° C. cooler than when we started. And if air could thus rise from the surface to ten times this height, say the top of the troposphere (about 7 miles for England), the temperature would drop nearly 100° C. Such a lapse-rate would not occur with moist air, because, as the moisture is precipitated out by the cooling, the latent heat of steam-condensation (p. 236) to some extent compensates this adiabatic fall of temperature while cloud is being formed.

As we have seen (p. 233), the vapour pressure of water is lower the lower the temperature, so that if the original moisture content which the air carried exceeds this reduced value, when the air is cooled to any temperature, the surplus moisture must come out as a cloud of liquid water—viz., to the saturation point of the cooled air (dew point). The cooled air has now

only that amount of water left in it which corresponds to the lower value for the vapour presure. In other words, a cloud will begin to form at that level, at which the water content (whatever it happens to be) just exceeds the vapour pressure corresponding to the reduced temperature, for that level. But if the current of air goes on rising, still more moisture will separate out as the temperature continues to fall. The cloud, therefore, will go on increasing in height, but its base level will not alter so long as the moisture content of the air supply does not vary.

All sorts of clouds at different heights, up to about 7 miles in the latitudes of Europe, are formed in this way, and if the question is asked, Why does this rise of air take place? the answer is to be found in solar radiation, either directly or indirectly. For example, the sun might so heat a patch of ground, which absorbs radiation more freely than the neighbouring region, that the air above it is heated and expanded to a point that its density is relatively reduced; it would then rise like a balloon, though in much less regular fashion, the denser air constantly pushing in beneath and displacing it, with much turbulent and rolling effect due to friction. This effect of any fluid rising, because its density is lower than that of its surroundings, is the well-known phenomenon of *convection*, and, of course, it is a very familiar effect everywhere. The "balloon" of air will go on rising (and partly mixing with neighbouring air) till its buoyancy is lost, for as it self-cools by expansion, there must come a time when the density difference vanishes as compared to its surroundings at the higher level; the cloud then ceases to rise. If the initial density-difference is very great, and the initial humidity considerable, the air will rise to much greater heights than usual, especially if the upward rush is maintained by a moist supply from below.

Huge quantities of water may be thus precipitated out and come down in thunder-rain, accompanied by hail when the uprush has caused a big drop in temperature in the upper regions. Whether any cloud produces rain or not will of course depend mainly on the amount of moisture in the rising air. So long, in fact, as the moisture particles are small their rate of fall is

so small (see Stokes' law, p. 406) that they are carried upward, but when they increase, the rate of fall increases, and at certain size the rate of fall just balances that of the rising air through which they are falling and they remain stationary—*i.e.*, in the vertical sense; whilst any larger particles, whose rate of fall exceeds that of the rising air, will fall as rain.

General Circulation of Air.—Although, as explained, the sun may be directly responsible for rising air masses, more frequently the effect is indirect, by acting through the general circulation of the earth's atmosphere. Considering the earth as a whole with the sun's rays impinging upon its spherical surface, it is easy to see that the absorption by rocks, plants, water, etc., will be greatest in equatorial regions and least in polar regions, because of the average angle at which these rays strike the ground or sea—the nearer this angle is to a right angle the more gain there will be by absorption and the less loss by reflection. So that in general the equatorial regions will be hotter than the polar; and, of course, this is true of other planets, like Mars, whose axis of rotation is more or less vertical to the plane of the ecliptic.

But this is not all the story. When the sun's rays strike the earth obliquely as they do in temperate zones, and as they always do near sunrise or sunset, the amount of radiation reaching ground level is greatly reduced by another factor—namely, atmospheric absorption. It will be easily understood that in these cases the heat rays have to traverse a length of hundreds of miles of atmosphere, the journey being greater because it is curved and not a straight line, owing to the effect of refraction; and although dry air is wonderfully transparent, moist air is relatively opaque. Moisture, which is always present even in dry desert regions, and also dust, from which the air is never free even over the ocean reaches, cut out quite a considerable amount of solar radiation not only by absorption but also by scattering. The net result of these effects should be that the upper air (stratosphere) should be colder and the lower air and earth's surface warmer at the equator, whilst over the regions of high latitude the reverse should hold. As a matter of fact, the stratosphere over the polar regions is

50° C. warmer than that over the equator, though the surface temperature may as much colder.

The relatively high temperature, found in the very outermost confines of the atmosphere, seems to be greatest over equatorial regions, though this has not been yet explained. At any rate, it is now fairly clear that the stratosphere, the undisturbed rarefied and serene atmosphere lying above the churned-up lower regions below (troposphere), has not actually a constant temperature as was once supposed, but a temperature changing slowly with height, in the opposite direction to that which obtains with the troposphere. With the latter, *because* it is churned up more or less continually by convection (being heated mainly from the warmed earth below), the temperature falls with increase of height. It is true it does not fall to the full adiabatic extent of about 10° C. per kilometre rise; this is because the churning is incomplete and because heat-intake is not excluded, since the troposphere itself absorbs some of the heat rays of the sun and earth. In fact, the average lapse-rate is only something like 6° C. per kilometre at low levels and about 7·5° C. at high levels of the troposphere; and, as can be imagined, since the troposphere represents the churned portion of the atmosphere it reaches much greater heights at the equator (about 10 miles) than it does in the middle latitudes (about 7 miles); while at the poles it is much less.

Now in the stratosphere, which is the upper portion of the atmosphere resting on this disturbed troposphere, the heat intake is not derived to any appreciable extent from below, but mainly by absorption and scattering of solar radiation above, and so the outside (uppermost) layers are the warmest. For example, at the equator the bottom of the stratosphere (top of troposphere) has a temperature of about 195° absolute (at about 10 miles height); but as the higher regions are explored the temperature rises steadily until at a height of 36 miles it is about 303° absolute (30° C.) according to Lindemann and Dobson.

The exploration of the upper air has been very helpful in tracing out the general circulation of the atmosphere over the globe, but even now this is only imperfectly understood.

Neglecting the complication of local and surface circulations, there appears to be a general continuous drift of air in the troposphere from the west, in both North and South Hemispheres above latitude 30°, whilst the direction is opposite in the equatorial belt. The first or circum-polar drift from west to east makes it appear as if an atmospheric shell were rotating in the same direction as the earth itself, but rather faster, so that to anyone on the solid ground it seems to be moving as a wind of say 20 miles an hour. But in addition to this movement from west to east there is a component of motion, equivalent to a gradual drift towards the two poles, probably to feed the so-called polar anticyclones, or regions of high pressure. These can be roughly pictured as a cap of cold air (in each case) sending out a reverse drift or supply of cold air from east to west, with a general tendency towards the equator. This polar easterly drift, however, is a surface one, while the westerly drift near the poles is an upper one, so that in north polar regions we have a tendency (apart from local considerations) to east and north-east winds below, with west and south-west winds above; each opposite drift being independent and the upper one supplying the general air-feed for the lower one. On the other hand, in middle latitudes the entire drift, down to the surface, is westerly (apart from local circulations), but there is a region between the polar and middle latitudes where these opposed drifts of air (the westerly relatively warm and moist, the easterly cold and dry) come into conflict. The northern Atlantic and the north-west of Europe, for instance, constitute such regions of conflict, as do the latitudes of the so-called "roaring forties" in the Southern Hemisphere; and such regions are particularly the birthplaces of storms and cyclones (see p. 373).

It is not easy to account for all these movements in the world circulation, but they are evidently connected with temperature differences between equator and poles. As the surface air over the poles is cold, while the upper is relatively warm (p. 369), the air is more dense near the polar surface than the air over the equator. The effect of this, as can be shown mathematically by the adiabatic laws, is to cause atmospheric pressure

over the cold regions to be more concentrated at lower levels than is the case in warm regions. That is to say, at a high level the pressure is higher over the warm regions than it is over the cold at the same level; or, putting it more precisely, the pressure-lapse with height is smaller over the equator than it is over the poles. Here the air collects, as it were, in a dense pool at the surface.

So it comes about that, at high levels over the earth's surface, there is a steady fall of pressure, for any particular level, towards the poles where it is lowest, though the total pressure (surface) at the poles is relatively high. Now air at high pressure always tries to move to any place where the pressure is low, and so there will be a tendency for the upper air of low latitudes to flow to the poles. It cannot do so directly because of the rotation of the earth which deflects it to the east. This will be appreciated when it is remembered that the velocity of rotation (as say miles per hour) of any object on the earth's surface is greatest at the equator (about 1,000 miles per hour), just one-half at latitude 60°, and zero at the poles. So any object starting to move say due north from the equator, endowed with this extra horizontal component as it travels to more slowly-moving parts of the earth's surface, will soon be deflected in an easterly direction; and eventually if it gets far enough it will appear to be coming from the west. Conversely any object starting to move from the North Pole, will, in its southerly movement, soon be left behind (as it were) by the earth and appear to be coming from a north-easterly and finally easterly direction.

This is exactly what happens with the wind spreading outwards from the cold, dense air at the poles, impelled towards southern mid-latitudes by higher pressure; such wind quickly acquires a direction towards the west, and the force of these easterly winds, mainly derived from the above effects of the earth's rotation, may be enormous. We shall see later that it is similarly the earth's rotation which makes the wind, spreading outwards from any local region of high pressure (anticyclones) move circularly around them, with only a small component leaking directly outwards; and the wind drifting inwards into

any region of low pressure (cyclones) is similarly deflected, but in the opposite direction, so that it mainly flows circularly round instead of directly filling up the low pressure area.

We are now in a position to understand how it comes about that masses of air are so frequently rising by displacement from below (apart from direct convection due to solar heating), and thereby producing cloud, with or without rain. For in the movements of air outlined above it frequently happens that cold, dense air, near warm, light, and moist air, undercuts it and lifts it bodily off the ground. This happens in England on the northern side of advancing cyclonic depressions, where there is usually a north-east or east wind at the surface and a south-west wind above, sliding over it and continually rising. This gives gloomy weather, with thick clouds and often steady rain. On the other hand, on the south side of the centre of the depression, the air is rising for another reason—namely, because it has a lower pressure and density than the air further south; as wind blowing continually from the south-west, the air is also gradually displaced upwards, while southern air drifts in. This usually gives cloud, intermittent rain, and drizzle. On the western side of the depression there may be a very sharp line of discontinuity, where a veritable wall of cold air of polar origin comes tumbling down, as it were, and undercutting the air of southern origin. This usually produces violent effects—squalls, more or less severe, and heavy rain showers, the so-called "clearing showers" that precede the relatively fine weather in the rear of the depression, where the cold, clear air of polar origin comes in from the west or north-west (p. 375).

It will be therefore realised that any conditions that lead to atmospheric instability or strong convection must cause bad weather. Normally the atmosphere is fairly stable because the temperature lapse-rate (p. 369) is well below the adiabatic, and any undue rise by convection is promptly checked by adiabatic cooling. But if for any reason the upper air is unusually cold or the surface air unusually hot, while the upper air is normally cold, so that the lapse-rate exceeds the adiabatic, instability results, with more or less violent convectional effects. When the upper air is warmer than usual, as it is with the

central regions of anticyclones, conditions are stable, and only slight convection can occur for the reason just given; in such cases it is possible to have surface air in summer heated by the warm ground, without appreciably rising to form cloud, while on a cold winter night the surface air may be cooled many degrees below the temperature of the air, a few hundred feet above.

Weather Forecasting.—In spite of the immense labours which have been devoted to the study of atmospheric circulation, the present-day position of meteorology is far from satisfactory, if long-date forecasting be taken as the criterion. Even the origin of cyclones and anticyclones, which more or less dominate the weather from day to day, is as yet imperfectly understood. A cyclone or depression was recognised in the nineteenth century as an area in which barometric pressure is below the average, the lines of equal pressure (isobars) being closed, in more or less circular form as seen in weather-maps, those of lowest pressure being in the centre. Such a system, which generally drifts (in high latitudes) eastward, is associated with more or less wind and cloud or rain, the wind blowing circularly in a counter-clockwise direction, but with an inward tendency near the earth's surface—*i.e.*, towards the centre. An anticyclone has an opposite structure of closed isobars, more or less circular, with the pressure highest in the middle; wind blows in a clockwise direction, with an outward tendency near the earth's surface. The weather associated with an anticyclone (which is often approximately stationary) is fine, especially in the middle, though there may be much cloud or even rain in the outer regions of the lower pressure. The above wind directions of cyclones and anticyclones refer to the Northern Hemisphere; in the Southern the directions in each case are reversed. Broadly speaking, we may say in the Northern Hemisphere that when the high pressure is to the south the wind is from the west, while when the high pressure is to the north the wind is from the east. The law of Buys Ballot states the case completely by saying that if you stand with your back to the wind low pressure is on your left.

These two main types of atmospheric circulation appear all

over the earth's surface, but they are now recognised as only incidents in the general circulation of the earth's atmosphere. There can be no question that cyclones in the middle or high latitudes, of both the Northern and Southern Hemispheres, are born in the conflict between the two opposing currents referred to on p. 370. The idea, which prevailed in the nineteenth century, that cyclones were caused by an uprush of warm moist air has been abandoned in the twentieth century because this hypothesis is not in accord with observed facts. The modern conception is due to V. and J. Bjerknes, the Norwegian meteorologists (father and son), and their view, which matured during the Great War, is sometimes called the "polar front theory." Briefly it is that the birth of a cyclone, which for England is generally away out on the Atlantic, follows on the wave front separating the warm westerly (or equatorial) air, on the south side, from the easterly or polar air on the north side of the line of discontinuity. This line or rather surface of separation is a wavy one, and a protruding tongue of equatorial air, the tip of which projects northwards into the polar air, begins the birth process. This wedge or tongue has a "warm front" on its easterly side, and a "cold front" on its westerly—that is to say, on the east side of the wedge the warm air is rising and sliding over the adjoining cold polar air, while on the other side the cold polar air (being more dense) is constantly slipping underneath the warm tongue. The rising air on the east side produces (by cooling) cloud and steady rain; the displaced air on the west side produces violent dislocation, with squalls, whilst in the middle of the tongue the westerly air may be rising and producing cloud or rain. It has been noted that cloud and rain are never produced except by the rising (and consequent cooling) of air carrying moisture, but it is not yet quite clear how the deficiency of air in the central regions, causing reduction of pressure, arises. During the above changes the cyclone definitely appears, with circular deflection of the air round the point of lowest pressure—*i.e.*, the point of the wedge. The cyclonic system follows the main drift eastwards, generally intensifying on its journey—*i.e.*, the pressure gradient becoming steeper and the wind accordingly

stronger. So, on the west or rear side of the cyclonic depression a stream of cold polar air which had originally come from the east curls round and blows from the north-west or west; and in the passage of such a cyclone over any spot, the change of temperature and wind direction, as well as force, is usually very marked when this polar air appears, thrusting its way in at the "cold front." After a few days' travel the warm sector or wedge is lifted bodily from the ground by the polar air which has pushed in, and the wedge is said to be "occluded." At this stage the depression becomes more or less uniformly cold at all points, its drift to the east ceases, and the wind gradually moderates as the depression fills in and the pressure rises to normal.

It is to be noted that such depressions do not usually appear singly, but drift, like eddies in a stream, in a usually north-east direction across the British Isles. Between each advancing depression, which brings bad weather, there is usually a wedge of high pressure, causing temporary fine weather; and the average line of the track of such successive cyclones skirts northern Ireland and southern Scotland. Very frequently, moreover, to the south of the main depression a smaller and often more violent disturbance, called a secondary depression, appears, similar in every way to, though smaller than, the main cyclone.

Climate.—There are some regions of the earth which are very stormy because they lie within the average track of the cyclones. Such a region is the North Atlantic stretching to Iceland and including North-West Europe, which is, therefore, subject to changeable weather. Other regions are favoured by more or less permanent anticyclones, such as the mid-Atlantic and Azores region. In winter there is one vast region of high pressure over Siberia, like a permanent anticyclone, due no doubt to the configuration of the land, which by radiation cools the superincumbent air and so increases its density. This huge pool of cold air is even colder (at the surface) and more steady than that of the North Pole, and it tends to flow outwards in all directions, but, of course, acquires a circular rotatory motion owing to the earth's rotation (p. 371). Offshoots of this cold

anticyclone give Central Europe, Scandinavia, and even Southern Europe the severe winters they often experience; and even England may feel their effects. But it is in November, when the Siberian anticyclone is becoming stabilised, and in May, when it is breaking up, that its influence seems most regularly to affect the English climate by producing cold snaps.

Indeed, the meteorology of England is so capricious that it is virtually impossible to say there is any regularity about it at all. There can be doubt of the existence of eleven-year rain cycles and the thirty-four year Brückner cycle, so far as the weather broadly is concerned; but these and other cycles which have been established by definite "correlation data" are largely swamped in England by what may be called chance effects, and it is these which make long-date forecasting impossible. Alexander Buchan undoubtedly recognised some annual periodicities, particularly the six "cold spells" *about* February 9, April 12, May 11, June 15, August 9, and November 9, as well as three warm spells; but none of these come with unerring regularity, except the cold spells of May and November, which rarely fail. And although it is not known definitely why, these two occurrences are connected in some way with the surface redistribution of the air in the Northern Hemisphere, when the Siberian system, in either forming or breaking up, establishes Icelandic or Scandinavian offshoots, which bring cold wintry conditions to Britain.

Such in very brief outline is the present-day position, but the realities are exceedingly complex. Forecasting nowadays is mainly based on a search for surfaces of discontinuity in the advancing depression, rather than on the old lines of predicting a sequence of changes likely to occur with its advance, dependent on assumed similarities of weather, for similar positions in the area of all depressions. Forecasting has undoubtedly improved with the new treatment, but owing to the kaleidoscopic changes continually occurring in local circulation, in a region like the Western Atlantic, the chance element must loom up very large.

§ iv. Pure Chemistry.

The composition of the earth, the nature of the individual "stuffs" out of which it is formed, and how these materials behave towards each other, were problems that exercised the brains of the alchemists from the days of Geber (p. 16), and although they had ever before their eyes two chief goals, the discovery of the "elixir vitæ" and the transmutation of the baser metals into gold, they could not help finding new materials in the course of their experiments. Many of the elements—*e.g.*, iron, copper, silver, gold, mercury, lead and so on—had been known from very early times, but others were gradually added to the list, so that, by the year 1800, some two dozen or more elements, in the sense we now understand the term, had been isolated from their compounds or found native. By 1850, largely owing to the discovery of new methods of analysis, for which men like Berzelius and Davy were responsible, the list had risen to well over fifty, and by the end of the century textbooks on chemistry furnished the student with the names and characters of at least two dozen more. Some of these, like cerium, gadolinium, samarium, scandium, etc., were very rare and little more than museum curiosities; still they had their interest in being yet other types of "brick" out of which the world was made. In our own generation the catalogue has been still further extended, sometimes by the addition of half a dozen at a time like the inert gases or by the cluster of unstable elements that have come to light in the study of radioactivity.

But the search for new elements has been less the goal of modern chemistry than the attempt to unify and co-ordinate the great mass of knowledge which steadily accumulated, viz., by the search for fundamental laws and the formulation of theories to explain these laws. At the beginning of the nineteenth century a tremendous stimulus to further investigation was given by Dalton's atomic theory, incomplete as it was. The fundamental distinction between acids and bases was already recognised though imperfectly understood. The work of Black (p. 166) on lime and magnesia, grouped among the "alkaline earths,"

followed by that of Davy (p. 143) on caustic soda and potash, grouped among the alkalis, had made it clear that all these so-called "bases" were oxides or hydroxides of metals which could neutralise acids, forming salts. On the other hand, chemists were misled by Lavoisier into believing that acids owed their character to oxygen, and so for a long time missed the essential feature—viz., hydrogen, replaceable by metals. It would be tedious and outside the scope of this book to trace out the slow and difficult steps, during the nineteenth century, or the successive theories which were discarded, before towards its close the real nature of acids, bases and salts was elucidated. Briefly the modern conception is based on the brilliant achievements of Arrhenius and van't Hoff who established the theory of electrolytic dissociation (or ionisation) to explain the many puzzling facts which research had brought to light. On this theory an acid like hydrochloric acid, HCl, is partly split up in solution into electro-positive ions, H^+, and electro-negative ions, Cl^-, the former cations, the latter anions. When the hydrogen is replaced by a metal, say sodium, giving sodium chloride or common salt NaCl, the latter in solution is similarly split up into the cation, Na^+, and anion, Cl^-. This feature (electrolytic dissociation or ionisation) is common to all acids and salts; whilst bases, like caustic soda, NaOH, in solution are ionised into a metal ion, like Na^+ and the anion group, hydroxyl, OH^- which is common to all of them. In these ions the sign $^+$ means that the atom has lost an electron, and the sign $^-$ that the atom (or group) has gained an electron.

The Classification of the Elements.—It was only natural that chemists should attempt to arrange the elements in some sort of order, in the hope of finding family relationships between them. One type of classification was based on the occurrence of some striking feature, arbitrarily selected; another scheme on some equally prominent characteristic; but when compared the two schemes might give quite contradictory results. For instance, a classification into gases, liquids and solids broke down at once when it was discovered that a gas, like hydrogen, could be both liquefied and solidified, and that a liquid, like mercury, could be volatilised and frozen. Obviously the ideal classi-

fication was that which took into account all characters, leading to a grouping of the elements where the members of each division had the largest number of points in common.

One method was to divide the elements into metals and non-metals, but that proved unsatisfactory, inasmuch as no hard-and-fast line could be drawn between them. To take one example only: hydrogen, one of the commonest of the elements, is a colourless, tasteless, odourless gas, and, without doubt, is obviously a non-metal; but on closer examination it shows itself possessed of some of the characters of a metal, especially by its ionisability in acids, like metals in their salts.

Another mode of arranging the elements is in accordance with their "valency," or saturation powers in combining with each other. Since the years 1850-60 valency has been a subject much discussed among chemists, originally by men like Kolbe, Kekulé and Frankland. It is fundamental and therefore important that we should gain some idea of the subject. The substances hydrochloric acid, water, ammonia and marsh gas are represented respectively by the formulæ HCl, H_2O, NH_3 and CH_4, which means that one atom respectively of chlorine, oxygen, nitrogen, and carbon combines with one, two, three, or four atoms of hydrogen; and seeing that no compound of hydrogen is known where the hydrogen is directly united to more than one atom of another element, it is spoken of as univalent, or monovalent. Chlorine in most compounds is similarly univalent. Oxygen unites with two atoms of hydrogen, and is therefore counted as divalent; nitrogen with three, and is trivalent; carbon with four, and is quadrivalent, or tetravalent. Other elements have higher valencies up to seven or eight, while some, the "inert" gases, decline to combine with any other element, and are therefore said to be non-valent. Valency thus expresses saturation-capacity and may be stated conveniently as a figure which, for a given element, defines the number of atoms of hydrogen or chlorine which combine directly with one atom of the element. If oxygen, which is normally divalent, is taken as the standard instead of hydrogen or chlorine the valency figure is twice the number of oxygen atoms which combine directly with one atom of the element—*e.g.*, carbon

TABLE OF THE ELEMENTS

A.N.=Atomic number; SY.=Symbol; D.D.=Date of discovery (approx.); A=Ancient; A.W.=Atomic weight—when O=16.

A.N.	*Name.*	*D.D.*	*SY.*	*A.W.*
1.	Hydrogen	1766	H	1·008
2.	Helium	1868	He	4·00
3.	Lithium	1817	Li	6·94
4.	Beryllium	1828	Be	9·02
5.	Boron	1808	B	10·83
6.	Carbon	A	C	12·005
7.	Nitrogen	1772	N	14·008
8.	Oxygen	1774	O	16·00
9.	Fluorine	1886	F	19·00
10.	Neon	1898	Ne	20·18
11.	Sodium	1807	Na	23·00
12.	Magnesium	1808	Mg	24·30
13.	Aluminium	1828	Al	26·97
14.	Silicon	1810	Si	28·00
15.	Phosphorus	1669	P	30·98
16.	Sulphur	A	S	32·06
17.	Chlorine	1774	Cl	35·46
18.	Argon	1894	A	39·94
19.	Potassium	1807	K	39·10
20.	Calcium	1808	Ca	40·09
21.	Scandium	1879	Sc	45·10
22.	Titanium	1825	Ti	47·90
23.	Vanadium	1801	V	50·95
24.	Chromium	1797	Cr	52·04
25.	Manganese	1774	Mn	54·95
26.	Iron	A	Fe	55·84
27.	Cobalt	1742	Co	58·95
28.	Nickel	1751	Ni	58·69
29.	Copper	A	Cu	63·55
30.	Zinc	1520	Zn	65·38
31.	Gallium	1875	Ga	69·72
32.	Germanium	1886	Ge	72·60
33.	Arsenic	A	As	74·93
34.	Selenium	1817	Se	79·20
35.	Bromine	1826	Br	79·91
36.	Krypton	1897	Kr	82·90
37.	Rubidium	1861	Rb	85·40
38.	Strontium	1808	Sr	87·63
39.	Yttrium	1794	Yt	88·93
40.	Zirconium	1824	Zr	91·20
41.	Niobium (Columbium)	1846	Nb	93·30
42.	Molybdenum	1783	Mo	96·00
43.	Masurium	1925	Ma	—
44.	Ruthenium	1844	Ru	101·55
45.	Rhodium	1804	Rh	102·90
46.	Palladium	1803	Pd	106·70
47.	Silver	A	Ag	107·88

TABLE OF THE ELEMENTS—*Continued.*

A.N.	*Name.*	*D.D.*	*SY.*	*A.W.*
48.	Cadmium	1817	Cd	112·40
49.	Indium	1863	In	114·80
50.	Tin	A	Sn	118·70
51.	Antimony	A	Sb	121·76
52.	Tellurium	1798	Te	127·50
53.	Iodine	1811	I	126·93
54.	Xenon	1898	Xe	130·20
55.	Cæsium	1860	Cs	132·81
56.	Barium	1808	Ba	137·37
57.	Lanthanum	1839	La	138·90
58.	Cerium	1803	Ce	140·20
59.	Praseodymium	1885	Pr	140·90
60.	Neodymium	1885	Nd	144·25
61.	Illinium	1926	Il	—
62.	Samarium	1849	Sa	150·40
63.	Europium	1896	Eu	152·00
64.	Gadolinium	1889	Gd	157·00
65.	Terbium	1843	Tb	159·20
66.	Dysprosium	1886	Ds	162·45
67.	Holmium	1886	Ho	163·50
68.	Erbium	1843	Er	167·60
69.	Thulium	1877	Tm	169·40
70.	Ytterbium	1878	Yb	173·00
71.	Lutecium	1907	Lu	175·00
72.	Hafnium	1923	Hf	178·60
73.	Tantalum	1802	Ta	181·30
74.	Tungsten	1778	W	184·10
75.	Rhenium	1925	Re	—
76.	Osmium	1803	Os	191·00
77.	Iridium	1803	Ir	193·00
78.	Platinum	1750	Pt	195·20
79.	Gold	A	Au	197·20
80.	Mercury	A	Hg	200·60
81.	Thallium	1861	Tl	204·30
82.	Lead	A	Pb	207·20
83.	Bismuth	A	Bi	209·00
84.	Polonium	1900	Po	210·00
85.	(undiscovered) provisionally Eka-iodine	—	—	—
86.	Niton (Radon)	1900	Nt	222·00
87.	(undiscovered) provisionally Eka-cæsium	—	—	—
88.	Radium	1898	Ra	225·95
89.	Actinium	1900	Ac	—
90.	Thorium	1828	Th	232·15
91.	Protoactinium	1918	Pa	—
92.	Uranium	1842	U	238·10

N.B.—This Table gives the list of elements as ordinarily found in Nature. Many of these elements are not "pure," but are mixtures of isotopes (p. 256) of different atomic mass (each practically an integer). The number of these isotopes among the radioactive elements (84-92) is considerable, and in these cases only the principal isotope is listed.

is tetravalent—in the compound CO_2, calcium divalent in $CaCl_2$ or CaO, and so on.

Some elements, however, are not constant in their valency. Thus phosphorus may combine with either three or five atoms of chlorine, and the same variability is true of many other elements. Frankland, more especially, studied this aspect of the question, and concluded that this inconstancy in valency depended on external conditions. As a result the classification founded on valency alone is unsatisfactory; further, it has been found that elements of the same valency may differ in almost every other respect. Contrast, for example, the opposite types of element sodium (univalent) and chlorine, which is generally univalent.

The basis of the modern classification of the elements is atomic number (p. 249), plotted in periodic sequence, to be described presently. For purposes of reference the table given on pp. 380, 381 gives the names, symbols, atomic weights, atomic numbers and approximate dates of discovery of all the elements at present known. It will be noticed in this table that hydrogen is given an atomic weight, 1·008 and not 1. The original reason for assigning this strange figure, instead of unity, to the simplest element was to make O=16·00 exactly instead of a number slightly below this, as it is if H=1, and as oxygen appears so frequently in chemical compounds, this unit (exactly 16) made weight-calculations, based on chemical formulæ, simpler. Later research work on the constitution of atoms has justified this procedure, since as we have seen (p. 253) all elements which are "pure," and all individual isotopes of "mixed" elements (p. 256), have atomic weights which are almost exactly whole numbers (multiples of 1) if the atomic weight of the standard, hydrogen, is taken as 1·008. And this is evidently because, when Nature created the elements by condensation of hydrogen nuclei (protons) with electrons, the process was accompanied by the liberation of energy, which as we have seen (p. 296) means loss of mass—energy and mass being interchangeable in Nature's magic crucible. Thus for example, when four hydrogen atoms weighing 4·032 are transposed into one atom of Helium, the weight of this atom is 4, the remaining mass being emitted as

energy or lost radiation. How, when and where (whether at stellar temperatures or at the absolute zero of interstellar space) such genesis of the elements arises, is not yet clear; but it is certainly not yet within the power of man to achieve. It will be useful now to sketch very briefly how the modern classification of the elements has been arrived at.

In 1808 Dalton (p. 184) propounded his "atomic theory," which conceived matter as consisting of invisible and indivisible particles or "atoms," those for each element having a definite weight, representing the combining weight. In the early years of the century every element was regarded as composed of independent single atoms only, *i.e.*, the smallest free units; for the term "molecule," though suggested by Avogadro in 1811, did not come into recognition until long afterwards. Avogadro said there were two kinds of primary particles, *molécules intégrantes*—*i.e.*, molecules as we now understand the term—and *molécules élémentaires*, which corresponded to Dalton's atoms. That hydrogen could unite with oxygen was universally admitted, but that hydrogen could unite with hydrogen or oxygen with oxygen, to form pairs of atoms, respectively, as the real free units, was not realised until later as we have seen (p. 242). In 1858 the Italian chemist, Cannizzaro, wrote an important treatise on the whole subject, which he called "A Sketch of a Course of Chemical Philosophy," in which he upheld the doctrine preached by Avogadro—viz., that equal volumes of all gases, at the same temperature and pressure, contain equal numbers of molecules, "not," he said, "an equal number of atoms, since molecules of the different substances or of those of the same substance in its different states may contain a different number of atoms, whether of the same or of a different nature." In this way, through Cannizzaro's great genius, chemists at last stumbled on the truth and recognised that matter in its free state, as we commonly meet it, exists and reacts chemically or physically in the form of units or molecules, which normally consist of groups of atoms and not free atoms. That is, like compounds, the molecules of which are made up of two or more atoms of *different* elements linked together, elements consist of

molecules made up of two or more of the *same* atoms linked together. Many of the elementary molecules consist (as gases) of groups of two atoms like H_2, O_2, Cl_2, etc., some of three, like O_3 (ozone), but some more than three; whilst some notable cases occur, like mercury, Hg, of only one atom to the molecule, and all the inert gases (helium, argon, neon, krypton, etc.) are similarly mon-atomic. Cannizzaro also formulated a revised set of atomic weights corrected to the new basis, and showed that the laws of organic chemistry were identical with those of inorganic, although the contrary belief had for long been an obsession among chemists. "There is only one chemistry and one set of atomic weights," was one of his favourite aphorisms.

The Periodic Law.—As far back as 1817 Döbereiner, professor of chemistry in Jena, found that many of the elements could be arranged in threes, or triads, the members of each triad having similar chemical characters and possessing atomic weights having a certain numerical relationship to each other. Thus chlorine, bromine and iodine formed a triad with like properties, while the atomic weight of bromine was the mean of those of chlorine and iodine or very nearly so. Similarly calcium, strontium and barium formed a triad with similar chemical characters, and the atomic weight of strontium was nearly midway between those of the other two.

The next step was taken by the English chemist, Newlands, who, in 1864, discovered that when the elements were arranged in order of their atomic weights, and when any particular element was selected as a starting-point, the eighth element above it in the series possessed the same characters as the one from which the start had been made, like notes at octave intervals on a pianoforte keyboard. This, Newlands called the "Law of Octaves," but for various reasons chemists did not take kindly to this important discovery. Yet, five years afterwards, a similar "Periodic Law" of the elements was published by a much greater man, the famous Russian chemist, Mendeléeff.

Mendeléeff was born in 1834 at Tobolsk, in Siberia, where his father was what we would call a Director of Education. In 1856 he became a lecturer in the University of St. Petersburg, as

it was then called, and two years later professor, a position he held until 1890, when he resigned to take up the duties of Director of the Bureau of Weights and Measures. He died in 1907.

In his paper on the Periodic Law, published in 1869, he tells us how he arrived at it. "There must be some bond of union," he says, "between mass and the chemical elements; and as the mass of a substance is ultimately expressed in the atom, a fundamental dependence should exist and be discoverable between the individual properties of the elements and their atomic weights. So I began to look about and write down the elements with their atomic weights and typical properties, analogous elements and like atomic weights on separate cards, and this soon convinced me that the properties of the elements are in periodic dependence on their atomic weights." As Mendeléeff's table is printed in every textbook on chemistry, it is unnecessary to repeat it here, more especially as it has undergone considerable modification of recent years, owing to our knowledge of the structure of the atom, acquired since his time. Without going into detail, the general principle may be illustrated in the following way.

If we look at the table of the elements on pp. 380, 381, and put the names down in the order of their atomic numbers, beginning in the first row with the inert gas, helium, and the second row with the next inert element, neon, the third with argon, and so on, we arrive at the series begun below.

In this series the figures stand for atomic numbers, but it is to be remembered that Mendeléeff based his sequence on atomic weights and not atomic numbers, which at that time were not recognised. This, however, makes practically no difference since the atomic number order is the same as that of atomic weights with few exceptions. It should also be noted that the inert gases of the first column of the (incomplete) series below—*i.e.*, He, Ne, A, etc.—were not then known. But he clearly brought out the repetition or periodicity of similar properties, evinced by the elements in the vertical columns of his famous table.

First row—	He 2	Li 3	Be 4	B 5	C 6	N 7	O 8	F 9
Second row—	Ne 10	Na 11	Mg 12	Al 13	Si 14	P 15	S 16	Cl 17
Third row—	A 18	K 19	Ca 20, etc.					

It will be seen that in the first vertical row we get an association of inert elements; in the second column, Li, Na and K are closely allied in chemical properties, and similarly with the third and succeeding columns. As the table becomes more complicated further on, we need not pursue the subject; enough has been given to illustrate the principle underlying the law.

In one interesting paragraph in Mendeléeff's paper he says, referring to conspicuous gaps in his table due to undiscovered elements: "The discovery of many yet unknown elements may be expected, for instance, elements analogous to aluminium and silicon, whose atomic weights would be between 65 and 75," and, sure enough, these elements which he had provisionally called eka-aluminium and eka-silicon, afterwards called gallium and germanium were discovered in 1875 and 1886 respectively, and their atomic weights came within Mendeléeff's predicted limits. His bold prediction of the properties of several other, as yet undiscovered, elements gave a great stimulus to chemical research; the predictions were verified as the new elements were discovered, and at the present moment there are only two gaps to be filled in (atomic numbers 85 and 87). Except these, no new elements remain to be discovered, though new isotopes may yet be found of known elements, and it is possible that elements higher than atomic number 92 (uranium) may yet be found. If ever found they would probably be very unstable radioactive elements, and Jeans as we have seen (p. 309) believes that they exist in great quantity in stellar material; so that the disruption of such hypothetical elements, with liberation of radiant energy, explains the great loss of mass which the sun and stars are believed to have suffered in the past (p. 330) and even the enormous stores of energy (mass) which they still radiate away into space.

The recognition of the Periodic Law raised once more the question of the origin of the elements, and resuscitated the idea put forward by Prout in 1815—viz., that the atoms of all the elements were condensations of various numbers of hydrogen atoms. Stas's accurate atomic weight determinations, however, negatived this idea, but, as we have seen (p. 283), all later

research has gone to confirm the essential truth of Prout's conception.

The Carbon Compounds.—In spite of Cannizzaro's insistence on the fact that "there is only one chemistry," it has been and still is the custom to divide the science into two main sections, Inorganic and Organic, the latter centring on the element carbon. For that reason organic chemistry is often called "The Chemistry of the Carbon Compounds." Of course, the element carbon takes part in the formation of very many inorganic compounds also, such as calcium and potassium carbonate; but numberless carbon compounds are associated with life, either directly or indirectly, life in the far past, as in the case of coal and mineral oils and their derivatives, or, in the present, as constituents of animals and plants, the proteins, carbohydrates and fats. Many of such bio-chemical compounds have been synthesised in the laboratory, beginning with the waste product of the animal body, urea, which was synthesised by Wöhler in 1828. This historic synthesis is important, in that it disproved the old doctrine of "vital force," which laid down that organic compounds could not be produced chemically, but only by the intervention of life.

It was well known to the chemists of the middle of the nineteenth century that carbon was a quadrivalent element, and could hold on, so to speak, to four atoms of a monovalent element such as hydrogen. Thus, the substance marsh gas, or methane, CH_4, could be represented by the formula with four "links":

$$\begin{array}{ccccc} & & H & & \\ & & | & & \\ H & — & C & — & H \\ & & | & & \\ & & H & & \end{array}$$

The carbon atom with its four saturation-valencies or four links was then said to be "saturated," as it could not be induced to take up any more hydrogen atoms than four.

This method of expressing the formulæ of compounds, as diagrammatic expression of the structure of their molecule, as was first introduced by Couper in 1858, when Kekulé first recognised the tetravalency of carbon. The method, later

applied to organic compounds in enormous numbers, is called the "linking of atoms," and its adoption gave a tremendous impetus to the development of Organic Chemistry.

These links or bonds joining the atoms together to form molecules are a pictorial representation of the affinities, in which it is assumed that a link stands for mutual saturation of the valency of one atom by the valency of another; and as the number of valencies for carbon is 4, whilst those for H, O, N, etc., are respectively one, two, three, etc., it will be readily understood that all manner of formulæ could be constructed on paper, which might or might not represent the actual molecular structure of real compounds. It is, therefore, perhaps not surprising that this wonderful theoretical instrument was destined to stimulate experimental investigation, which ultimately enabled chemists to build up synthetically a vast array of new carbon compounds and elucidate their molecular structure, as well as fix the constitution of hosts of naturally occurring substances.

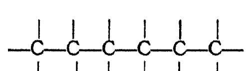
During all this great extension of Organic Chemistry it was found neither necessary nor profitable to enquire into the nature of the links, binding the atoms together in all these compounds, for the reason that until the twentieth century such enquiry was merely speculative, without experimental basis, and because chemists could get on perfectly well without such knowledge. And even now when the nature of the binding has been more or less "explained" by invoking electronic forces, chemists for the most part are content to preserve their simple pictorial, non-committal, structural formulæ for ordinary use. At the same time it is desirable to state briefly what the new views are, as indicated by the discoveries in Atomic Physics and by X-ray analysis (p. 229).

Bragg has shown how carbon atoms are disposed in the crystal of diamond (pure carbon), and this gives the key. The atoms are so arranged in the lattice or framework, that every carbon atom is surrounded symmetrically by four other carbon atoms. This is not in the least surprising, for it had long ago (1874) been deduced by le Bel and van't Hoff from purely chemical considerations. Indeed, a whole new branch

of knowledge (stereochemistry — p. 446) dealing with the arrangement of atoms in space had been built up on the simple assumption that the four valencies of carbon were directed symmetrically from the centre of a sphere, to the four corners of an imaginary tetrahedron (p. 27) inscribed within the sphere.

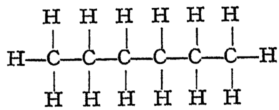
Whilst, therefore, modern observations entirely confirm earlier theoretical conclusions, this does not help us in understanding what the valency bonds really are, or how they bind the atoms so securely together in the molecules of compounds. In this respect we are still to some extent on speculative ground, but the modern theory is, that when atoms are singly linked a valency-electron (p. 251) of one atom somehow joins forces with a valency-electron of another atom, and the two electrons (moving, no doubt) form a *pair* between the atoms. It is this pair of electrons which constitutes a single link. Thus, to return to methane, CH_4, each of the four valency-electrons of the carbon atom joins up with the single valency-electron of four hydrogen atoms, forming four pairs of electrons, lying symmetrically about the carbon atom at the four corners of an imaginary tetrahedron. It still remains unexplained why this should be, or how these pairs preserve their mean positions while in motion; and, as will be imagined, the case becomes complex when less simple compounds are considered or when the so-called "double link" (p. 392) is present. We must leave this intricate problem and pass on to consider how, on the simple conception of linking of atoms, molecular structural formulæ can be built up.

Now if, say, six carbon atoms be linked together in a row or "chain," one valency (or link) each of contiguous atoms mutually "saturate" each other, giving the skeleton—



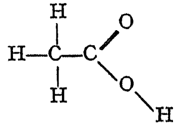
The terminal C-atoms will have three links left free to unite with hydrogen atoms, while the remaining four will have two only. When these fourteen valencies are saturated by fourteen hydrogen atoms, we obtain a structural formula

showing how the six carbon and fourteen hydrogen atoms are linked together, in a molecule of the hydrocarbon, C_6H_{14} (hexane):



Such a type of formula clearly expresses the constitution of the compound, and therefore is called a constitutional or structural formula; whilst formulæ like C_6H_{14}, which merely express the numbers of atoms in the molecule, are called *empiric* formulæ. Hexane has a type of structure similar to that of a large number of carbon compounds, called the aliphatic series, including paraffins, fats, oils, etc. But many organic compounds are much more complex in structure, than this simple type (hexane) selected for illustration. Their synthesis has been effected step by step in such a way as to prove their constitution; and the elucidation of the actual mode of atom-linking in the molecular structure of hundreds of thousands of such compounds is indeed one of the noblest triumphs of modern science. There still remain however large numbers of complex bio-chemical compounds, whose synthesis has not yet been accomplished.

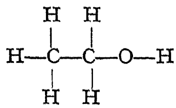
Returning to methane and similar hydrocarbons, we can replace H by a group consisting of one carbon atom, two oxygens and one hydrogen, a combination group or "radical" known as "carboxyl," and get the so-called series of the fatty acids, each member of the series depending on the number and linkage-mode of carbon atoms present in it. Thus:



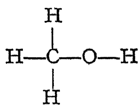
is acetic acid. If there are four carbon atoms in the chain we get butyric acid, the substance present in rancid butter; if there are sixteen carbon atoms, palmitic acid, the acid obtained from palm oil, and so on

Or again, if we replace a hydrogen atom by a combina-

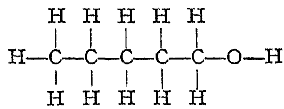
tion group of one oxygen and one hydrogen (known as the radical hydroxyl, OH), we enter on the series of the alcohols. Thus,



is ordinary alcohol, or ethyl alcohol, while the formulæ,

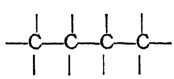
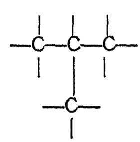


and



give the structure of methyl alcohol and amyl alcohol respectively. The latter, however, is only one of several possible amyl alcohols, all $C_5H_{11}.OH$. For it is possible to link these atoms together in several different ways. This phenomenon, of different structure (and properties) for the same numbers of atoms in the molecule, is very frequent among organic compounds, and is known as *isomerism.* Isomeric compounds possess the same empiric formula, but a different constitution and different properties.

The possibility of isomerism among organic compounds will be appreciated best by considering a simple case, such as the different modes by which four carbon atoms can be linked together, so as to satisfy the tetravalency of each atom. It will be readily seen that only two skeletal frameworks are possible—viz.:

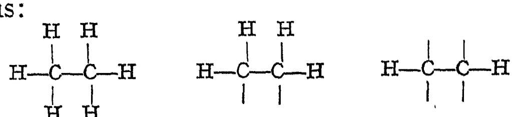
(1)  and (2) 

So that we can predict that there can be two hydrocarbons C_4H_{10}, *and only two,* derived by the saturation of the ten available links in each case with hydrogen. Two such hydrocarbons are known, and only two: one whose structure is built up of a simple chain (1), and called normal butane; the other, called iso-butane, having the branched or side-chain structure (2).

But a moment's reflection will show that the number of possible modes of atom-linking will increase rapidly as the

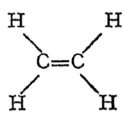
number of carbon atoms in the skeleton increases, and so, of course, the number of isomeric hydrocarbons possible. Indeed, the possible number becomes vast when there are say fifteen carbon atoms; and when it is considered that these hydrocarbons are the parents of numberless derivatives, obtained by replacing one or more hydrogen atoms by other atoms or groups, and that there are many alternative positions for these "substituents" to take up, it will be realised that the number of possible isomers among organic compounds approaches the infinite.

It is not necessary that the available free linkages, left over after joining the carbon skeleton together, should be satisfied by hydrogen. Pairs of unsatisfied valencies may appear as in the case of ethylene (C_2H_4) or acetylene (C_2H_2), which we can contrast with the saturated hydrocarbon, ethane (C_2H_6) thus:



Ethane Ethylene Acetylene

Such types of compound—and there are many of them—are called *unsaturated* compounds, and it is usual to express the formulæ by a double link or triple link respectively, as if the free valencies saturated themselves mutually, thus:

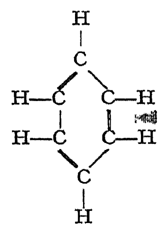


and H—C≡C—H

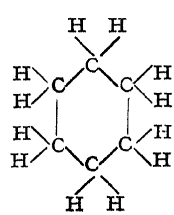
This is a convenient device to signify unsaturation and the particular pair of contiguous carbon atoms (say in a long chain) which are unsaturated. Saturated hydrocarbons are called paraffins (Lat. *parum affinis*) because they have all their affinities equalised, and so are very inert chemical substances compared to unsaturated compounds which, by tending to become saturated, are chemically reactive.

In 1825 Faraday discovered a substance which he called "bicarbonate of hydrogen," and which he obtained from a deposit in vessels used in the manufacture of gas from oil,

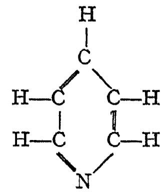
with which the streets of London were, at that time, illuminated. This parent hydrocarbon, which we now call benzene, has six carbon and six hydrogen atoms in its composition, that is to say the empiric formula C_6H_6. Benzene in properties appears to be saturated, but it can be induced to accept six more hydrogen atoms, twelve in all, not fourteen as in hexane. This peculiarity remained a puzzle until 1865, when the German chemist, Kekulé, at that time working in the chemical laboratory of St. Bartholomew's Hospital, London, hit on the idea of closed chain or ring structure. Thus by linking the ends of the skeleton formula of hexane, shown on p. 389—*i.e.*, uniting the loose ends into a ring—and by doubling the links of alternate carbon atoms he obtained the now well-known "benzene ring," thus:



This forms the basis of the molecular constitution of a host of carbon compounds known as the Aromatic Series which include aniline dyes, certain explosives, synthetic drugs, etc. There is no difficulty in seeing how such a ring containing six carbon atoms may fix a total of twelve hydrogen atoms and no more, for all that is necessary is to add one more hydrogen atom to each carbon, by breaking the three double links and making them single. We then have two hydrogen atoms attached to each carbon giving the substance hexa-hydro-benzene (cyclohexane), when each carbon atom will be saturated thus:



Ring structure or cyclic grouping leads to many other types of series; thus when a trivalent nitrogen atom is substituted for one of the carbon atoms in the benzene ring, we get pyridine as is shown in the formula:



With these three ideas of skeleton structure in his hands—(1) the carbon chain (Aliphatic Series), (2) the carbon ring (Homocyclic, including Aromatic Series) and (3) the ring containing carbon as well as one or more foreign atoms, like nitrogen (Heterocyclic series)—it is possible for the chemist to build up, theoretically, all sorts of compounds, and also actually to synthesise them with wonderful diversity in the laboratory.

General Reactions and Synthesis.—It is necessary now to refer briefly to a few types of universal chemical change, because these general reactions are fundamental to chemistry, either for purposes of synthesis or in relation to life.

In 1836 Dumas showed that a hydrogen atom of a paraffin could be replaced by a chlorine atom with production of hydrogen chloride as a by-product. This type of reaction, known as *substitution*, the laws of which, as formulated by Dumas, met with a good deal of opposition at the time, applies also to chlorine or iodine. The simplest example of substitution can be written as an equation thus:

$$\underset{\text{Methane}}{CH_4} + Cl_2 = \underset{\text{Methyl chloride}}{CH_3.Cl} + HCl$$

and by further substitution it is possible to replace the remaining hydrogen atoms, giving successively the compounds CH_2Cl_2, $CHCl_3$ (chloroform), and CCl_4.

To illustrate the utility of substitution, let us take another simple case. Just as methane gives methyl chloride, so the paraffin ethane, C_2H_6, gives ethyl chloride, $C_2H_5.Cl$. Now as we get to more complex cases it becomes rather inconvenient

to use constitutional formulæ in equations, so *rational* formulæ are generally used, these being, as it were, shorthand for the full structural formulæ (generally using dots in the place of links, and omitting them when obvious). We can therefore write ethane $CH_3 \cdot CH_3$, and ethyl chloride $CH_3 \cdot CH_2 \cdot Cl$, both of which rational formulæ imply clearly enough how the atoms are linked.

When ethyl chloride is treated with water ($H \cdot OH$) in a suitable way, HCl is formed, and the chlorine atom substituted by the hydroxyl group (OH), giving $CH_3 \cdot CH_2 \cdot OH$, which, as we have seen (p. 391), is common alcohol. Now this is a very simple but interesting thing, for we have thus in two steps synthesised an important organic compound; and since the starting-point (ethane) can be obtained from acetylene ($CH \vdots CH$) by suitable treatment with hydrogen, and since acetylene is formed from carbon and hydrogen at the temperature of the electric arc, as was first shown by Berthelot, it follows that ethyl alcohol can be indirectly built up or synthesised from its elements. And what is true of alcohol is true of all organic compounds (several hundred thousand) which have been synthesised—ultimately they can be built up from the elements composing them, and the steps by which this is done indicate their structure.

A very notable difference distinguishes unsaturated from saturated compounds in their behaviour with chlorine, bromine, and iodine (the halogen elements); for instead of "substituting," unsaturated compounds add a molecule of the halogen. For example, ethylene (p. 392) rapidly takes up chlorine, the double link becomes single, and ethylene dichloride $CH_2Cl \cdot CH_2Cl$ results. Moreover, unsaturated compounds add many other substances as well as halogens, and this general reaction (*addition*) has proved of great service in synthesis.

Oxidation is a general type of change implying either the taking up of oxygen (as, for example, when iron rusts and forms a hydrate of ferric oxide, Fe_2O_3), or the removal of hydrogen (generally only partially). In organic chemistry oxygen gas (O_2) is not generally used, because it is not sufficiently active, but as oxidising agents such substances are used as readily

part with some of their oxygen (like nitric acid, HNO_3, potassium permanganate, $KMnO_4$, etc.). Thus by suitable oxidation ethyl alcohol gives first acetaldehyde ($CH_3{\cdot}CH : O$) and then acetic acid ($CH_3{\cdot}CO{\cdot}OH$), the first stage involving removal of hydrogen and the second the taking up of oxygen. Incidentally, we have synthesised a fatty acid (acetic) which, like all organic acids, contains the typical group—$CO{\cdot}OH$. Oxidation plays a very important part in the chemistry of life, as we shall see later.

Reduction, which is the opposite of oxidation, involves the taking up of hydrogen or elimination of oxygen. For example, when acetylene (p. 392) takes up four hydrogen atoms, it is said to be reduced to ethane, and all unsaturated compounds behave similarly; those with a double link take up two, and those with a triple link four hydrogen atoms. But this must not be taken to imply that ordinary treatment with hydrogen gas will cause such reduction; as a rule special so-called "reducing agents" are employed, bodies which are themselves easily oxidisable in the process. Nevertheless, hydrogen gas can be used, as was indicated by Sabatier and Senderens, if suitable metals are present, like finely divided nickel, to activate the hydrogen and function as so-called catalysts. We will refer to catalysts again (p. 447), and for the present it is sufficient to say that they are agents which somehow hasten an otherwise sluggish chemical reaction. This kind of reduction with hydrogen, using metallic catalysts, is of great importance in the manufacture of margarine from oils. The latter contain derivatives (glycerides or fats) of fatty acids, some of which, like oleic acid, are unsaturated, and when they take up hydrogen by reduction, they give saturated fats which have a higher melting-point. By this process ("hardening of fats"), regulated carefully, oils are converted into fats of the consistency of butter.

Condensation is a term implying the linking together of two molecules by eliminating something between them, generally a molecule of water. We will illustrate this important type of synthetic reaction by considering the case of an acid and an alcohol, say acetic acid and ethyl alcohol. When

these two are mixed together, nothing apparently happens at first, but after a while it is found that a new substance is slowly appearing, called ethyl acetate, which has a sweet, fruity odour. This substance is one of a similar class, called esters, derived by the elimination of H_2O between the OH group of the alcohol and the CO·OH group of the acid, and the formula of ethyl acetate is $CH_3 \cdot CO \cdot OC_2H_5$. The reaction leading to esters is greatly accelerated if there is present a little "mineral" acid, like HCl, which functions as a catalyst, but the change is never complete. Here we have an example of a *reversible reaction*, the nature of which is explained on p. 399. It will be noted that esters are derived from acids by the replacement of the carboxylic hydrogen atom by some group like C_2H_5. In this sense they resemble salts, like sodium acetate $CH_3 \cdot CO \cdot ONa$, and indeed, esters were once called ethereal salts. But they differ from salts by the fact that they are not ionised, and they are quite different in properties. The simple esters are found naturally in fruits and some perfumes, whilst those esters which are derived by condensation of glycerol (p. 436) and complex fatty acids are the natural fats and oils (glycerides), as we shall see later.

Hydrolysis is a type of chemical reaction exactly the opposite of any condensation process involving elimination of water. That is to say, as the name indicates, hydrolysis means the splitting of any compound into simpler molecules by the assimilation of the elements of water. Suppose, for example, we take some pure ethyl acetate and shake this sweet-smelling, colourless, mobile liquid with pure water. A portion of it will dissolve, giving a neutral solution, and apparently nothing else happens; but, on standing a long time, it will be found that the watery solution is no longer neutral; it is acid, so turns litmus red, and this acidity, due to production of acetic acid (along with alcohol) increases with time. The hydrolytic fission can be written:

$$CH_3 \cdot CO \cdot O \cdot \overbrace{CH_2 \cdot CH_3} + H \cdot \overbrace{OH} = \underline{CH_3 \cdot CO \cdot OH} + CH_3 \cdot CH_2 \cdot OH.$$

And again here, as before with condensation, the velocity of the change is greatly increased by having present a little

strong inorganic acid, which (mainly by its hydrogen ions) functions as a catalyst and remains unaltered at the end.

Now here it may be remarked that there is something contradictory. How can, say, hydrogen chloride favour two opposite reactions (condensation and hydrolysis) at the same time? To clear up this apparent difficulty, let us dispense with the hydrogen chloride, which, after all, is not necessary to either change, but only hastens both, and consider the slow opposite reactions themselves. The key to the difficulty is found in the recognition of mass influence. This was first clearly demonstrated by the researches of Guldberg and Waage in 1867, when they showed that many chemical reactions, such as "double decomposition" with salts, are reversible, and that the extent of change in either direction is dependent on the mass—*i.e.*, number of molecules. Consider, for example, the case of two salts mixed in strong aqueous solution, say sodium nitrate and potassium chloride, where double decomposition gives rise to potassium nitrate and sodium chloride in the reversible change:

$$NaNO_3 + KCl \rightleftarrows NaCl + KNO_3.$$

In the solution we have, after mixing, all four salts present (apart from the four ions Na^+, K^+, Cl^-, and NO_3^-), and the extent to which the reaction proceeds in either direction (indicated by arrows) is determined by the number of the reactant molecules in unit volume—*i.e.*, upon their concentration. This is the meaning of Guldberg and Waage's mass law, which amounts to this, that the velocity of any reaction is partly governed by the *concentration* of the reacting substances. It must always be remembered that we are not dealing with single isolated molecules, such as appear in an equation on paper, but with myriads of them; and large battalions conquer.

For example, let us suppose in the above case that the solution is so strong (or, say, is cooled from a hot, strong condition) that the least soluble salt, which is potassium nitrate (KNO_3), separates out as crystals, because there is not sufficient water to hold it all in solution. This would cause a decrease in the concentration of one of the components on the

right-hand side of the equation, and so lower the velocity of the change in the direction shown $\longleftarrow$; therefore more $NaNO_3$ and KCl would go over in the direction shown $\longrightarrow$ as KNO_3 separated out.

We can thus manufacture potassium nitrate (saltpetre) from sodium nitrate (Chili saltpetre) and potassium chloride; and there are many similar applications of this principle, such, for instance, as making all manner of insoluble salts by precipitation.

Such reversible reactions of double decomposition are practically instantaneous, because they are between ions, which are formed with extreme rapidity from molecules of salts. This is not the case with acetic acid and alcohol, but the reaction, which is slow, can be written as a reversible equation of equilibrium:

$$\underset{\text{Acid and alcohol}}{CH_3{\cdot}CO{\cdot}OH + C_2H_5{\cdot}OH} \underset{\text{hydrolysis}}{\overset{\text{condensation}}{\rightleftharpoons}} \underset{\text{Ester and water}}{CH_3{\cdot}CO{\cdot}OC_2H_5 + H_2O}.$$

Both direct and reverse reaction are very slow. Even under the catalytic influence of a strong acid they are slow, compared to the ionic velocities of double decomposition. Nevertheless, the mass law holds good; the velocity in either direction is determined by (1) an affinity factor which is constant, and (2) the reacting masses, which change with time as the concentration (*i.e.*, number of reacting molecules in a given volume) changes. At first, starting from the left-hand side of the equation, the concentration of acetic acid and alcohol will be at a maximum, and so the reaction in the direction $\longrightarrow$ will be relatively rapid; but as their concentration inevitably diminishes whilst that of ester and water increases, this velocity diminishes whilst that in the direction $\longleftarrow$ increases. After a long time it must come about that the velocities of the opposing reactions are just equal; and when this is the case, equilibrium is established, in which there are as many molecules of acid and alcohol being condensed in unit time as there are of ester being hydrolysed by water. On the other hand, if an ester is hydrolysed in presence of an alkali, the process is complete, because the alkali neutralises the acid as fast as it is formed. This is

the well-known process of "saponification" by boiling with caustic soda, so called because it has long been in use (since ancient times) in the splitting of fats into glycerol and fatty acids as their sodium salts (soap—see p. 437).

Hydrolysis or saponification (the terms nowadays usually connote the same thing) is also of great importance in biochemistry, since, as we shall see later, it underlies the complex changes involved in the digestion of food.

Diffusion.—About the beginning of last century John Dalton made the interesting discovery that if he filled two bottles, one with hydrogen and the other with carbon dioxide, and united them by means of a long glass tube, the hydrogen bottle being uppermost, the lighter gas, hydrogen, passed gradually into the lower bottle and the much heavier carbon dioxide ascended into the hydrogen one, and that this diffusion continued until the two gases were equally mixed in both vessels. Dalton concluded that the gaseous particles were in constant motion, striving to get as far away from each other as possible, each quite indifferent to the presence of the other. The "atoms" of the gas were conceived as bombarding the walls of the containers in their efforts to escape, thus creating a pressure on the walls. On this conception rests the "kinetic theory of gases" (p. 224). In 1859 Clerk Maxwell calculated the speed at which the gaseous molecules were moving, and deduced the pressure of a gas on the wall of the container under varying conditions, thereby enabling us to understand the mechanism of diffusion.

As by the kinetic theory the average speed of the molecules, for a given temperature, is inversely proportional to the square root of the molecular weight, it follows that the speed of diffusion, say through some porous membrane through which the molecules can pass, will thus depend on the weight of the molecules, since diffusion depends on the rapidity of their movements. And since, as we have seen (p. 242), the density of a gas (at any definite temperature and pressure compared to hydrogen) is equal to half its molecular weight, it follows that the rate of diffusion of a gas, for any definite temperature and pressure, is inversely proportional to the square root of its density. This

is Graham's law of diffusion, from which, of course, it follows that hydrogen has the highest diffusion rate of all gases; but at the same time it must be remembered that the rate of diffusion of any gas increases with rise of temperature, because, as we have seen, the molecular speed is increased.

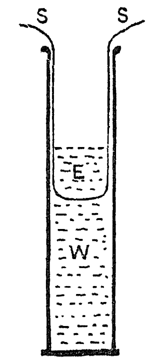


FIG. 110.—DIFFUSION OF LIQUIDS.

Diffusion also takes place between liquids, but, as might be expected from the kinetic theory, far more slowly than with gases, because the attractive forces between the molecules of each liquid, and their smaller "free path," make it more difficult for them to insinuate themselves between each other. If a jar is half filled with water (Fig. 110, W), and a fine silk cloth, S, is pushed into the jar so as just to touch the water, and then a dilute solution of an aniline dye, E, be very gently poured on the silk, the cloth being slowly withdrawn as the coloured solution is added, it will be found that the water below and the colour will remain apart for some considerable time. Gradually, however, the liquid in the jar will assume a uniform tint throughout, pointing to a slow mutual diffusion between the water and the dye solution. Care must be taken not to shake or otherwise disturb the jar, and to keep it at a uniform temperature, otherwise convection currents will accelerate the mixing.

Strange as it may seem, diffusion may also take place between solids. If, for example, a plate of copper and one of lead be firmly clamped together, so that the surfaces of the two metals are in the closest possible contact, it will be found that, after a year or more, the molecules of the copper and lead have intermingled at the plane of union. Diffusion in fact is very slow in the solid state, more rapid with liquids and most rapid with gases, as would, of course, be expected on the kinetic theory.

Solution and Adsorption.—But solid substances dissolved in liquids readily diffuse owing to the movement of their molecules. If, for example, strong brine (salt solution in water) is covered carefully with pure water, the latter being lighter floats on

top, but in time the salt from below will diffuse upwards into the water, and eventually the solution will have the same strength (concentration) all over. The process of diffusion does not stop here, the molecules still keep moving about though there is nothing now to indicate it, of course; it is important to recognise this incessant movement of dissolved molecules, as so-called "solute," among moving molecules of solvent, a movement which prevents these molecules separating out and sinking to the bottom, if they are heavier than those of the solvent, or rising to the top if they are lighter.

An important reservation, however, must be made here with regard to the movement of solute molecules, which in any solution (say in a closed bottle) keeps the concentration unchanged throughout its bulk, no matter how long it may stand. It is that, strictly speaking, this uniformity of concentration only applies to the bulk and not to the surface of contact with another solid (say the glass of the bottle) or with the air. Speaking generally, there is an increased concentration or local assembly of solute molecules at such surfaces, in layers which are only "skin deep" as it were, generally a single layer of molecules. But this increased concentration at surfaces, which is so small a thing in a bottle of solution, becomes of enormous importance if the surface happens to be very great; as it would, for example, if, instead of glass walls merely, we had suspended in the solution some solid powdered so finely that the particles had a diameter of only say ·01 μ (see p. 259).

Or again, to consider another aspect of the same problem, if instead of having a flat surface at the top exposed to air, we churn it up with air so as to make a real froth like soap lather, we greatly increase the surface between air and solution. This increased surface due to subdivision will be better appreciated by the reader if he imagines a cube, each of whose twelve edges is 2 inches long, divided by two transverse cuts into smaller cubes each of 1 inch edge. There will be eight of such smaller cubes, each having a face of 1 square inch. Now there are six square faces to every cube, and each face of the original large cube has, of course, an area of 4 square inches (2×2),

so that our large cube has a total area of 24 square inches (6×4). Similarly each of the eight smaller cubes has an area of 6 square inches, so that the total for all of them is 48 square inches (8×6). So that on dividing our larger cube by two transverse cuts we have *doubled* the total original area. The same kind of thing applies to all subdivision, as, for example, when we powder a solid substance by grinding it in a mortar or mill; and when the grinding is very fine there is an enormous increase effected in the total surface. When the state of subdivision is such as to give small particles beyond the power of ordinary grinding, such as have a diameter of say $\cdot 02\ \mu$, the increase in surface is really prodigious, so great in fact that the phenomena we are now describing predominate. In such cases the local concentration at these extended surfaces, called "adsorption," may be so great that very little of the solute is left in true solution at all, most of it being concentrated on the scattered particles, whether solid or gas.

The whole subject of adsorption has been very thoroughly worked out and formulated into mathematical expressions which we cannot consider here. It is sufficient to say that the phenomenon is intimately connected with that of *surface tension*, a condition of skin-like stretch of the molecules of liquids at their free boundaries. All liquids show such a skin of stretched molecules at the boundary surface in contact with air, and this skin enables certain insects to walk freely on the surface of sheets of water, or may prevent a needle lightly laid on the surface from passing through and sinking. Different liquids have different values for surface tension, which, moreover, may be altered by temperature changes or by dissolving certain substances in them. Most salts increase the surface tension of water, while soap reduces it; and, in fact, it is this reduction which gives soap its cleansing (detergent) qualities, by enabling oily films to be dispersed into minute emulsified drops, owing to the reduction of the tension between aqueous and oil layers. In the living cell, too, there are extended surfaces presented by the colloids present (p. 405), and the varying surface tension here plays a great part in biochemical processes. These, however, are highly complex and beyond the scope of this book.

Crystalloids and Colloids.—If a soluble substance like potassium nitrate is added to water it dissolves, and this means that free-moving molecules of the nitrate, as "solute," are distributed among the water molecules, as "solvent." If more potassium nitrate is added the dissolution proceeds, until a time arrives when it takes place more and more slowly and finally ceases. The solution is then said to be "saturated." If heat is applied the dissolution begins again, until, when the liquid is boiling, it again ceases, and another saturation point is reached. As the liquid cools the reverse process occurs, and crystals of potassium nitrate separate out; and if the solution is left to evaporate, all the salt (potassium nitrate) that was originally added to the water will crystallise out unchanged.

It should be recalled here that a salt (p. 378) in the inorganic chemical meaning of the word, is a substance derived from an acid by replacing the ionisable hydrogen of the acid by some metal. Thus nitric acid, HNO_3, yields nitrates as salts, like potassium nitrate, KNO_3; sulphuric acid, H_2SO_4 two classes of salts, one, acid sulphates like $NaHSO_4$ and the other neutral or normal sulphates, like Na_2SO_4, where Na stands for an atom of sodium. The most characteristic generic feature about salts is their ionisability when dissolved in water, a property that enables their solutions to conduct electricity and function as "electrolytes." Just as an acid in solution is partly ionised—*i.e.*, split up into positive H-ions (hydrions) and negative ions (anions), so salts are (more completely) ionised in solution into metal ions (cations) and the same anions as the corresponding acid. A solution of potassium nitrate therefore contains not only molecules of KNO_3, but also ions of K (each an atom which has lost an electron) and ions of NO_3 (groups of atoms each of which groups has gained an electron). This process of ionisation increases as the dilution increases, and is regarded as complete at infinite dilution. The ionic theory of solution founded by van't Hoff and Arrhenius in 1886 was the outcome of experiments on osmosis described on p. 410, but it came as a great shock to chemists at the time, all of whom even at the present day do not accept the theory in its entirety.

Early in the nineteenth century it was recognised that

there was a very marked difference between the diffusion-rate of substances, which could assume a crystalline form in the solid state, and those which did not crystallise. The first to study the diffusion of soluble substances was Thomas Graham, who was professor of chemistry in University College, London, from 1837 to 1855, when he took over the duties of Master of the Mint. In 1849 he gave an account of his discoveries, in which he showed that certain substances in solution passed readily through an animal or vegetable membrane, such as bladder (by dialysis), while others did not do so, or did so extremely slowly. The first of these two kinds of substances Graham termed "crystalloids" and the second "colloids." The crystalloids included all bodies capable of taking on a crystalline form in the solid condition, while colloids—so named from the Greek word *kolla*, or glue—were substances like gelatine, albumin, etc., which swelled up in water, but never actually formed a solution. Graham's apparatus for demonstrating the characters of these two types of bodies is known as a dialyser (Fig. 111), and consists of a jar, B, containing pure water, D, in which is suspended a bell-jar, A, whose bottom is composed of bladder or parchment, containing the colloid or crystalloid, E.

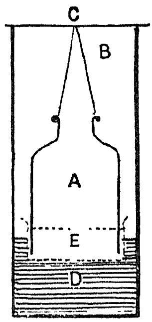


FIG. 111.—DIALYSER.

Sols and Gels.—Since 1900 immense progress has been made in elucidating the nature of colloids in solution, and this has been mainly due to the researches of Wolfgang Ostwald since 1908, following the invention of the ultra-microscope by Zsigmondy about 1903. It had long been known that while solutions of crystalloids were optically clear, those of colloids were either opalescent or turbid, and as such they were not regarded as very interesting by the chemists of the nineteenth century, who mostly avoided them in their zeal for dealing with pure substances. It was also known that such colloidal solutions did not clear by settling when allowed to stand, like ordinary suspensions, that some of them were slightly viscous, and that many such turbid solutions could be cleared when coagulated by addition of certain electrolytes.

It was not until the twentieth century when study was directed to small magnitudes that their nature was elucidated by the extension of the kinetic theory, and an entire new field of physical chemistry opened up. The limit of resolving power of the best microscope is about ·2 μ (·0002 mm.). The ultra-microscope depends on transverse illumination and renders visible, as points of light scattered by particles optically different from the liquid in which they are suspended, particles as small as ·005 μ, which is only about ten times the diameter of average molecules. In fact, turbidity, which is the result of optical scattering by such small particles, and regarded once as rather an unpleasant thing to be avoided, became the very means by which the nature of colloidal solutions could be studied.

And Brownian motion (p. 203), once so puzzling, was at last recognised to be the erratic zig-zag movement of very small, but relatively large, suspended particles incessantly bombarded by the still smaller molecules of the solvent, endowed with the kinetic energy which, as we have seen (p. 229), all liquids possess.

And so it came to be recognised that there was really no sharp dividing line between suspensions of large particles, on the one hand, in a liquid, and small ones, on the other—it was all a matter of particle size. There is an important law, first formulated by Stokes in 1850, governing the rate of fall of any spherical particle through a gas or liquid medium, and the important point about this law is that, other things being equal, the rate is proportional to the square of the radius. So that, for example, if a particle of small radius fall 1 millimetre per second in a given liquid another particle of the same substance $\frac{1}{100}$ of its diameter would fall at the rate of $\frac{1}{10000}$ millimetre per second. This is negligibly slow, but nevertheless not infinitely slow, as it is with colloidal solutions—*i.e.*, suspensions of exceedingly small particles. There are, in fact, other forces at work besides Stokes' law in such cases—viz., (1) continual bombardment of the particles by the liquid molecules, as we have seen, and (2) electrical charges (either all + or all –) on the particles; these by repulsion tend to keep them apart.

This last factor, which was unsuspected at first, is indeed the principal one which prevents the particles coming together, by those attractive affinities which were discussed (pp. 227, 228) in considering kinetic energy. The moment the electrical charge is destroyed or neutralised in any way, say by adding the right kind of electrolyte (charged ion), the particles tend to agglomerate together into larger particles (coagulation or clotting), which then settle more or less rapidly by sedimentation.

Further research has made it clear that there are two very distinct kinds of colloid solutions or "sols," as they are now called—viz:

(1) Suspensoids.
(2) Emulsoids.

(1) Suspensoids are, as their name indicates, suspensions of excessively fine solid (and therefore crystalline) particles such as metals like gold and platinum, which can be got into "solution" in water, as permanent sols, by means of a powerful electric discharge under the water.

(2) Emulsoids, as their name indicates, are suspensions of excessively fine oil drops in water or aqueous solutions, or conversely of fine water drops in oil solutions.

In each case the suspended matter is said to be in the *disperse phase*, while the solvent is the *continuous phase*; but it is to be noted that it is among group (2) that high viscosities are usually observed, owing to mutual friction between the two liquid phases, exactly like what is observed in ordinary emulsions. Indeed, there is no sharp line of demarcation between emulsoid sols and ordinary emulsions, such as are got by shaking an oil with water, containing a little soap or something else which prevents the oil drops from coalescing together. Milk is a natural emulsion in which the particles of fat (butter) are of moderate size, greater than in emulsoid sols. So the cream slowly rises to the surface, being lighter than the solution of calcium caseinogenate, milk sugar (skim milk) etc., in which it is suspended; and cream itself is a fairly stable emulsion which is only with difficulty made to coagulate or clot into butter by churning (facilitated by

hydrogen ions due to lactic acids, produced by the fermentation of milk sugar—see p. 445).

In addition to sols, where usually the disperse phase is relatively small in amount, there are *gels*, where it is relatively great and the continuous phase small. This gel (jelly) condition appears in the coagulated particles precipitated from sols; but it is more important in colloids like gelatine and biological cellular membranes, including food, leather, wood, etc. Here the discrete particles are not free, as in sols, but clotted together in the form of fine threads, network, or in some other way, in a disperse phase (water), whose amount may be relatively large or small.

It is worthy of note that the disperse and continuous phases responsible for colloidal phenomena are not necessarily confined to solids and liquids. A logical extension of the conception must naturally include froths and smokes. Froths and foams consist of excessively fine air particles, as a gaseous disperse phase, suspended in a liquid continuous phase; while smokes consist of fine solid or (more frequently) liquid particles suspended in air. In common smoke from coal fires the disperse phase is a complex liquid mixture (tar) in an exceedingly fine state, and accordingly kept in suspension by the kinetic energy of the air molecules, as well as by electrical charges; so that smoke-polluted air does not really clarify itself, and we must depend on rain for purification in the long run. Even pure air has been found to have an enormous number of unsuspected small particles suspended in it (fine solid debris, or dust, and evaporated salt particles from sea spray), as well as bacteria spores, etc.; and the optical qualities of the atmosphere (haze and visibility) partly depend on the number and nature of such particles, which serve as centres of adsorption (see p. 403) of water molecules contained in moist air.

An immense amount of knowledge has now been accumulated concerning colloids and surface tension phenomena, which we cannot even summarise here. It will be sufficient to say that this wealth of knowledge permeates into every aspect of biology, and the industries founded on it, because the three prime classes of chemical compounds associated with

the living cell—viz., the carbohydrates, the fats, and the proteins—function in the juices of the cell (whether vegetable or animal) as colloids and emulsions. And as our knowledge increases it is becoming more and more evident that chemical changes can occur at the greatly extended surfaces of colloid particles, such as would scarcely be dreamt of as possible in ordinary solutions. In these peculiar surface reactions, of which as yet relatively little is known, probably lies the key to many of the mysterious chemical manifestations of living protoplasm.

Osmosis.—Diffusion through a colloid membrane is something like separating small ashes from larger cinders with a riddle. The membrane acts as a sieve, allowing only smaller molecules or ions to pass through the network of its disperse phase (embedded in a continuous water phase); and the phenomenon of such diffusion through a colloid membrane is known as osmosis. It is of profound significance in the physiology of the living organism. The names associated with researches on osmosis are those of Pfeffer, professor of botany in Leipzig, and van't Hoff, professor of physics, first in Amsterdam and then in Berlin.

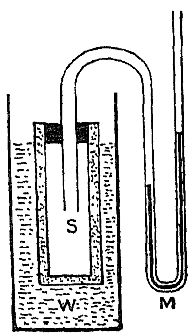


FIG. 112.—OSMOMETER.

Pfeffer's method, described in a paper published in 1877, consisted in using what is called a "semi-permeable membrane." When a drop of a solution of copper sulphate is brought in contact with a solution of potassium ferrocyanide, a reaction takes place between them which results in the formation of a colloidal film of copper ferrocyanide on the surface of the drop, which has all the characters of a semi-permeable membrane permitting the passage through it of some substances but not of others. The pellicle, however, is too delicate for experimental purposes, so Pfeffer hit on the plan of using a porous earthenware pot, in which he placed a solution of copper sulphate. He then plunged the pot into a solution of potassium ferrocyanide, with the result that a precipitate of

copper ferrocyanide was formed, in the pores of the wall of the pot (Fig. 112). After rinsing out the pot he placed in it a 10 per cent. solution of cane-sugar, S, and sealed it securely with an air-tight rubber stopper through which was fitted a manometer, M. The pot was then immersed in water, W, which at once began to enter through the wall, and the sugar solution, thus diluted, ascended the inner leg of the manometer, causing the mercury to rise in the open leg, thus indicating the pressure exerted by the sugar solution on the wall of the pot. This is called "osmotic pressure."

From the large number of measurements which Pfeffer made on the relative osmotic value of a variety of substances, van't Hoff, in 1887, demonstrated an exact correspondence between osmotic pressures in solutions and gas pressures. This osmotic pressure was found to be directly proportional to the strength of the solution, but it was observed, at the same time, that when the dissolved solute was an electrolyte (p. 255), especially if the solution was very dilute, and the molecules underwent ionisation (p. 378), each ion had the same osmotic value as an entire molecule. Thus, if the substance were potassium nitrate, KNO_3, the molecule splits into the ions K^+ and NO_3^-, the first electro-positive and the second negative, and each is equal in osmotic value to an entire undissociated molecule, KNO_3.

On the other hand, a substance, like cane sugar, which is not an electrolyte, behaves normally in solution, that is to say the osmotic pressure simply depends on the number of molecules; so they are not split up (ionised) and do not conduct electricity. It was on this foundation of the study of osmotic pressure and electrical conductivity that van't Hoff built up the modern ionic theory of solution and was able to calculate the degree of ionisation of electrolytes (*i.e.*, acids, bases and salts) at various concentrations; and the one salient fact emerged, that the distinguishing feature of all acids is their production of hydrogen ions in solution—the stronger the acid the greater the concentration of H-ions. A hydrogen ion is simply a hydrogen atom which has lost its electron. It is therefore a proton (p. 245) but not a free proton, since in some way it is combined

with the water molecules of the solution in which it is present.

Osmotic pressure increases with temperature, exactly as volume or pressure does with gases (law of Gay-Lussac and Charles, 1802). So that here in osmotic pressure we have an exact analogue in solution of what is happening to gases, as postulated by the kinetic theory. The dissolved molecules (say of cane sugar) exercise the same kinetic energy as if they were existent as a gas having the same volume and temperature as that of the solution. Just as the pressure of a gas is a function of its temperature and concentration (*i.e.*, number of molecules in unit volume), so the osmotic pressure of any un-ionised dissolved substance is the same function of the temperature and its *molecular* concentration.

van't Hoff's discovery was of vast importance to chemistry, for it demonstrated clearly that Avogadro's law of gases, which, as we have seen (p. 242), is the most fundamental thing in chemistry, is equally applicable to solutions. Therefore, just as Avogadro's law was the only means by which the molecular weights of gaseous substances could be arrived at (or substances which could be vaporised so that their gas density could be determined), so this extension of the law to solutions enabled the molecular weight of such substances (like cane sugar) to be determined (by their osmotic pressure) as could not be vaporised without decomposition. As this applies to large numbers of organic compounds, this law of osmotic pressure, together with a law discovered by Raoult, based upon it and relating the depression of freezing-point of a solvent to molecular weight of solute, gave an enormous stimulus to Organic Chemistry. Moreover, these laws provided a similar stimulus to physical chemistry, by furnishing an exact means through which the degree of molecular dissociation (ionisation) in solution could be calculated, in the case of acids, salts, and bases.

Let us consider two simple examples of osmosis, one taken from biology and the other from an industrial process (p. 414).

It is a well-known fact in vegetable physiology that every

plant contains, on ultimate analysis, twelve chemical elements combined in various ways to form proteins, carbohydrates, fats and so on. These elements are, using their chemical symbols for the sake of brevity, C, H, O, N, S, P, K, Ca, Mg, Fe, Na, Cl. Many other elements certainly do occur in plants, but these, with relatively few exceptions, are accidental, and not essential to the plant's well-being. Of the twelve elements mentioned, C, H, and O are by far the most abundant, as the following table shows (Ebermayer, 1882):

> *Wheat Grain.*—C, 46·1; H, 5·8; O, 43·4; N, 2·3; ash, 2·4.
> *Peas.*—C, 46·5; H, 6·2; O, 40·0; N, 4·2; ash, 3·1.
> *Potatoes.*—C, 44·0; H, 5·8; O, 44·7; N, 1·5; ash, 4·0.
> *Rye Straw.*—C, 49·9; H, 5·6; O, 40·6; N, 0·3; ash, 3·6.

(It should be noted that these figures are derived from an analysis of 100 parts of the plant substance dried at 100° C., so that all the uncombined water had been evaporated before the analysis was carried out.)

Carbon and oxygen are elements obtained by the plant from the air, all the rest being derived from soil-water. The acquisition of nitrogen from the air by some plants is a special case which is dealt with under biology (p. 418). The nitrogen in ordinary cases, and other elements (in the ash) are derived from nitrates, phosphates, etc., dissolved in the water absorbed by the roots, and an analysis of soil-water shows us that the solution, presented to the root, is exceedingly dilute—viz., about 10 to 15 parts of solid to 10,000 of water, or 0·1 to 0·15 per cent. The conditions are thus favourable to ionisation. In order to obtain the necessary salt ions the plant must therefore absorb far more water than it really requires, and the excess must be got rid of by what is called in vegetable physiology "transpiration," which may be defined as evaporation under protoplasmic control.

The agents, for the absorption of the dilute solution from the soil, are the root hairs which cover the terminations of the ultimate rootlets. These may be easily seen if some mustard seed is sown on a piece of moistened cloth or blotting-paper and examined after two or three days. The microscope shows

us that each root hair (Fig. 113) is a tube whose wall is a delicate membrane of cellulose, C, lined by a layer of protoplasm, P, and enclosing a cavity, V, more or less filled with a watery solution of various organic and inorganic substances, called "cell-sap," and having a concentration approximately ten times as great as that of the soil solution. In the root hair we have a natural dialyser, for the cellulose wall and the protoplasmic lining are both semi-permeable membranes, permitting the entry of the soil solution, but resisting the exit of the organic compounds in the sap. The consequence is a continued inflow of the dilute soil solution into the sap cavity, and a steady increase in osmotic pressure within the root hair. Excessive distension, and rupture of the hair, are averted by the withdrawal of the solution by cells in continuity with it, thus facilitating the entry of more soil solution. Further, the osmotic pressure keeps all the living cells distended or in a state of "turgidity," which is essential to cell growth. If a young growing cell be placed under the microscope and surrounded by a 4 per cent. solution of potassium nitrate, the cell will be seen to shrink (Fig. 114, 2). The explanation is that the natural conditions are now reversed; water is being withdrawn from the sap, and the elastically stretched cell wall contracts. If the external solution be raised to 6 per cent. (3) the protoplasm withdraws from the wall and the cell is then said to be in a state of "plasmolysis," and growth of the cell must cease since the constructive agent, the protoplasm, is no longer in contact with the cellulose membrane. If the external solution be raised to 10 per cent. (4), the protoplasm aggregates into a compact ball in the centre of the cell. The phenomena of plasmolysis were made great use of by Pfeffer and De Vries in the closing years

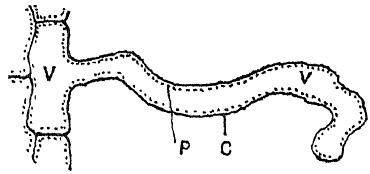


FIG. 113.—ROOT HAIR.

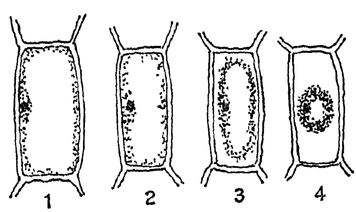


FIG. 114.—PLASMOLYSIS.

of last century when estimating the osmotic equivalents of various substances.

Bound up with osmotic phenomena in relation to protoplasm, is the no less important bearing of H-ion concentration on life-processes. Whether in the cell sap of plants, or the plasma of the blood of animals, or in water which sustains aquatic life, the hydrion concentration, or degree of acidity, is a controlling factor of supreme importance. Pure water, itself, dissociates (ionises) to a faint degree giving positive H-ions and negative ions of the group OH. Addition of alkali increases the concentration of the OH-ions, and reduces that of the H-ions to an infinitesimally small amount. Such liquids are alkaline, like a solution of caustic soda (NaOH). Addition of acids to water increases the H-ion concentration, but in all cases the product of the two concentrations (*i.e.*, of H multiplied by OH) is constant, and the same as the product for pure water. The symbol *p*H is now used in all branches of science to indicate the H-ion concentration of any liquid, but as the symbol involves a mathematical conception it need not be further explained. It is sufficient to say that in most natural fluids the H-ion concentration is very low but variable, according to the part which the fluid plays in biological phenomena, such as respiration, digestion, muscular effort, plant assimilation, etc., and how this variation is effected is one of the wonders of Nature.

Taking next an illustration from industry, it is well known that one of the chief sources of sugar is beetroot, and the problem before the manufacturer is to extract the sugar from among the host of albuminous and other colloidal substances present in the sap. Beetroot sap contains from 14 to 18 per cent. of sucrose—*i.e.*, cane-sugar—but the presence of all these other bodies interferes with its purification and crystallisation. The method adopted is to cut the root into thin slices and steep these in hot water, when the sugar and other crystalloids dialyse out into the water, leaving the colloids behind in the cells. By passing the extract through a series of tanks the solution is gradually concentrated, after which it is treated with certain chemical reagents which cause precipitation of all the con-

stituents save the sugar. The sugar solution, kept at the right *p*H, is then filtered and finally evaporated in vacuum pans, when the sugar itself finally crystallises out.

Applications of Modern Chemistry.—If we found it difficult to treat of the applications of modern discoveries in physics in the space at our disposal, it is simply impossible to perform the same service for chemistry. We must content ourselves with merely mentioning some of the chief lines in which recent discoveries have been applied to industrial processes.

In metallurgy, although the extraction of metals from ores is still carried out on the principles followed by the ancients, many improvements have been made and new methods introduced, such as electrolysis and very high temperatures in the separation of the rarer metals. Then there is the Bessemer process, of converting iron into steel, and its modern developments, and the utilisation of the slag as a source of phosphates for agricultural purposes; the employment of the rare earth oxides in the manufacture of gas mantles, and of potassium cyanide in the extraction of gold and silver from their ores. The old method of obtaining oxygen by the use of barium oxide has been supplanted by the fractional distillations of liquid air. Round the metal sodium cluster a whole series of industries, such as the manufacture of caustic soda and bleaching powder. The various alcohols, phenols, acetic acid, ethereal oils and essences, occur as groups of substances in the manufacture of which modern chemistry is deeply concerned.

When we add soap manufacture, the preparation of petrol, the so-called "cracking" of oils and the transformation of heavy petroleum into petrol, the fixation of atmospheric nitrogen by the several processes, the problems connected with the making of synthetic rubber, the huge aniline dye industry, following on the discovery of mauveine, the first coal-tar dye product by Sir W. H. Perkin in 1856, the synthesis of indigo by Baeyer in 1878, and, lastly, the manufacture of explosives, beginning with nitro-glycerine by Nobel in 1869, and ending with "T.N.T." (trinitrotoluol), amatol and tetryl during the Great War—when we think of all these and many other evolutions and applications of chemical research that have taken

place during the past fifty years, we must realise that any adequate account of even one section of them would require a volume in itself.

§ v. Modern Biology.

If we look back over the history of biology in the nineteenth century we cannot help being struck by the magnitude of the changes that took place in the science during the period 1845-70. It was in the course of these years that protoplasm came to be recognised as "the physical basis of life," both in the plant and in the animal; our knowledge of the lower forms of organic nature had been vastly extended as the microscope became an increasingly efficient instrument of research, and as microscopic technique steadily improved; vital phenomena received new interpretations as the chemistry of what came to be called "metabolism" received more and more attention; while the evolution theory entirely altered our conception of the inter-relationship of plants and animals, threw new light on the problems of adaptation of structure to function, and provided us with a clue to the proper understanding of hitherto puzzling facts both in adult morphology and in development. Indeed, it is no exaggeration to say that during the middle decades of the nineteenth century modern biology was born. We must now attempt to sketch, although necessarily in the briefest possible manner, a few of the more important discoveries that were made during and after these critical years.

The Life Histories of the Lower Plants.—We have seen how, in the early part of the century, botanists confined themselves very largely to the study of the higher plants, and how the various classifications that were put forward almost entirely ignored the lowest forms of vegetable life. The most that was accomplished was to divide them into three main groups, algæ, fungi and lichens, while between these and the flowering plants came a heterogeneous collection embracing mosses, ferns, horse-tails and their allies, whose life histories were either quite unknown or very imperfectly understood. By the middle of the century, however, the life-stories of many of these lower

forms had been traced out by various investigators, and, more especially, their sexuality had been established; although the connection between that phase in the humbler types of plant life and the corresponding process in flowering plants still awaited elucidation. That did not come about until 1850, when the great German botanist, Hofmeister, published his classic researches on "The Comparative Anatomy of the Higher Cryptogams."

Symbiosis and Lichens.—Among the lowest plants, the lichens attracted considerable attention about the middle of the century owing to a unique structural feature they presented. While in the main composed of a dense felt-work of colourless threads, or hyphæ, like those of a fungus, and bearing reproductive organs of the fungi type, they also contained green cells called "gonidia," meaning "offspring," and which were believed to be special kinds of propagative organs (Fig. 115). After a careful study of these bodies, the French botanist, Bornet, was able to show that they could be cultivated apart from the lichen, and were identical in type with the lower unicellular algæ. In 1868 Schwendener, professor in Berlin, asserted that the "gonidia" were really algæ on which certain fungi had become parasitic. Subsequently Reinke, professor in Kiel, suggested that the association was not one of parasitism but of "symbiosis," or "living together," with mutual benefit to each partner. Despite vehement opposition, the upholder of the dual nature of lichens won the battle, and before the end of the century lichens disappeared as a separate class, and its members were distributed among fungi in accordance with the nature of the fruit bodies they produced, which were recognised as purely fungal in character.

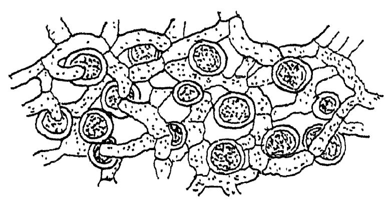


FIG. 115.—"GONIDIA" ENCLOSED BY THE HYPHÆ OF A LICHEN.

Similar cases of symbiosis were soon discovered, both in the plant and in the animal world. The greenish granules in the group of Protozoa, called Radiolaria, were also found to be

symbiotic algæ, as were also those in several other lower animals. Many forest-trees, heaths, orchids and other flowering plants were discovered to have fungi living in intimate union with their roots, the hyphæ of the fungus acting in place of the normal root hairs, which were absent. This type of symbiosis was called "mycorhiza," or "fungus-root."

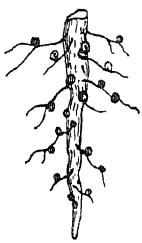


FIG. 116.—ROOT TUBERCLES OF THE BEAN.

Bacteria.—So long ago as 1540 the herbalist, Valerius Cordus, noted the occurrence of tubercles on the roots of lupins, but made no suggestion as to their function. More than three centuries afterwards the same tubercles were found to be always present on the roots of the great group of flowering plants known as Leguminosæ, to which peas, beans, vetches, clover and such-like plants belong, and at first they were regarded as pathological growths (Fig. 116). About 1887, however, it was discovered that the swellings were occupied by colonies of unicellular fungi, *i.e.* bacteria, which invaded the roots from the soil, and caused a sort of inflammation or "hypertrophy" in them. The bacteria (*B. radicicola*) were found to be able to fix the free nitrogen of the air, and thus accumulated in their bodies large quantities of that very essential element, which the host plant ultimately absorbed. This important discovery explained the value of the well-known agricultural custom of growing crops of lucerne and other leguminous plants on soil deficient in salts of nitric acid and ammonia, and "ploughing them in" instead of reaping them, thus providing a source of supply of nitrogen, for a succeeding crop incapable of forming such tubercles.

Since, then, about 1893, and principally owing to the researches of Winogradsky, other nitrogen-fixing bacteria have been discovered (*Azotobacter* and *Clostridium*), which inhabit the soil and in the absence of ammonia or nitrates may do useful service in indirectly supplying plants with nitrogen from the air. It is important to remember that all plants must have nitrogen if they are to grow, but that in the great majority of cases this nitrogen comes from nitrates in the soil, not from

nitrogen gas. Here again it was Winogradsky who showed how these nitrates are derived from ammonia, which itself results from the bacterial decomposition of nitrogenous excrement of animals or of dead plant remains. There are two distinct stages in the bacterial oxidation of ammonia, the first (1) brought about by a bacterium (*nitrosomonas*) giving nitrites (like KNO_2), which then (2) are oxidised to nitrates (like KNO_3) by another bacterium (*nitrobacter*). It is noteworthy that these two types of bacteria are "autotrophic," that is to say, as we have seen (p. 364), they build up their protoplasm entirely from inorganic materials—viz. CO_2 and NH_3—so long as magnesium and other inorganic elements are present; iron-bacteria (p. 364) appear to be similar, but other bacteria are parasitic, and can flourish only on suitable organic matter as foodstuff.

Bacteria and Disease—PASTEUR.—This reference to these minute unicellular forms of plant life leads us to consider the enormous development that has taken place, since 1880, in the branch of biology known as bacteriology. We saw (p. 67) how the Dutch microscopist, Leeuwenhoek, as far back as 1683, discovered what he called "animalculæ" in various fluids, putrescent and otherwise. In 1762 Plenciz, an Austrian physician, also studied the subject from the medical point of view, and went the length of saying that infectious diseases were caused by microbes floating in the air, and that each disease had a special microbe of its own. The whole subject was put on a scientific basis by the great French chemist and biologist, Pasteur, who from 1865 onwards showed that many of the phenomena, collectively called "fermentations," were due to the activities of micro-organisms. In 1877 he studied the cause of the deadly disease of cattle called anthrax, and succeeded in preparing a vaccine or infusion from the anthrax bacterium which, when injected into healthy animals, while it gave them the disease in a very mild form, rendered them immune to the severer type. It is thus to Pasteur that we owe the foundation of preventive medicine by inoculation—and the successful treatment of diphtheria, cholera, tuberculosis and a host of other more or less deadly ailments—thus leading

to a revolution in medical practice. Every surgeon in the middle of last century was only too well aware of the disastrous results that so frequently followed operations on the human body owing to the septic conditions set up in the wounds, but these untoward consequences were practically abolished by the introduction of the antiseptic precautions initiated by the famous surgeon, Lord Lister, who introduced carbolic acid (phenol) as a germicide.

The study of bacteria was greatly facilitated by the vast improvements made in microscope lenses and methods of sub-stage illumination at the end of the nineteenth century, and also by the use of aniline dyes which enabled the microscopist to determine structural details to a degree not previously possible. Culture methods of all sorts were also invented by Koch and others, and so it became possible to follow the life histories of various bacteria in the laboratory. The minuteness of these organisms was one of the chief difficulties that had to be contended with, and it was hard to realise that a speck of living matter, $\frac{1}{25000}$ inch in diameter (a cell, too, without definite nucleus), could produce such calamitous results.

Since Koch's time the study of bacteriology has opened up an immense field of knowledge concerning the nature of these microscopic plant cells which we call bacteria or bacilli. They are round-shaped (cocci), rod-shaped (bacilli), or spiral (spirilli), and their dimensions vary between as much as 60 μ and $\cdot 2$ μ, but the great majority are somewhere about 1 to 2 μ. Their function is not, like that of green plants, to make their own foodstuffs by the exercise of the chlorophyll function (which is absent), but to live parasitically upon other food (vegetable or animal), by digesting which they thrive and multiply, in a similar way to that observed among the fungi (which also are not green). There are a few bacteria, like those producing nitrates (see p. 419), for example, which are able to build up their food from simple inorganic substances like carbon dioxide and ammonia, but the great majority are either truly *parasitic*, (using the living host as source of food) or *saprophytic* (living upon dead organic material).

The saprophytic bacteria are found in enormous variety, and

they mostly discharge a very useful function in nature as scavengers, by destroying decaying and excremental matter of all kinds, whilst the other class (parasitic), also very numerous, are responsible for all sorts of diseases; though even here some of them, like *Bacillus coli* in the lower intestine, seem to perform a useful and harmless function. The disease-bacteria, such as *pneumococcus* in pneumonia, owe their deadly effect largely to the fact that, while they are flourishing, they chemically transform the proteins of the blood or body into substances which are acutely poisonous (toxins); but anyone in a normal state of health is able to resist these dangerous organisms by protective defences, since their white blood corpuscles (phagocyte or amœba cells) are able to destroy bacteria. When bacteria of any kind become isolated from the moist food material (substrate) upon which they live, and dry up, they usually protect themselves from extinction by forming minute spores, which are resistant to drought. Moreover, in many cases these spores are not killed by heating to temperatures (say 100° C.) which destroy the bacteria themselves. Such invisible spores, of the common bacteria and moulds or fungi, are always present in the air, and whenever they fall on a suitable moist food-material they bud, develop, grow and multiply. And the rate at which all these microscopic plants multiply is prodigious. A bacterium can divide into two every half-hour, and if that rate is maintained for twenty-four hours, a simple exercise in geometrical progression gives us the total number of progeny produced in that period as something like 70 million millions. Fortunately for us there are many conditions that prevent this appalling multiplication of small germs from being realised. A class of supposed bacteria, known as viruses, exist, so small (about ·025 μ) that they can pass through the exceedingly fine pores of porous porcelain and they cannot be seen with the highest powers of the microscope, although their effects are only too well known, as with the virus that is believed to cause smallpox for example.

We have already seen what an important part micro-organisms play in fermentation, indeed their activities have been exploited in many industrial concerns, such as wine and

beer making, cheese manufacture, tobacco-curing and so on. In Nature also they play most important rôles. They are Nature's scavengers, for it is due to them that the waste products of animal and plant life, as also their dead bodies, are broken up and decomposed, thus not only rendering such waste innocuous to the living, but bringing important constituents to the soil for the benefit of future generations of plants. Year after year we are learning more about the structure, life history and functions of bacteria, and the importance of the whole subject has justified the foundation of chairs of bacteriology in our universities; and the labours of hundreds of researchers has led to the production of an immense literature, extensive enough, indeed, to form a library of itself.

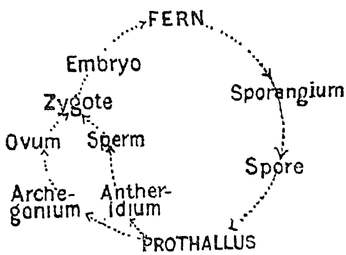


FIG. 117.—LIFE HISTORY OF THE FERN.

Life Histories of Plants.—About 1850 Wilhelm Hofmeister, professor of botany in Berlin, published a most important series of memoirs on the life histories of the higher cryptogams—viz., ferns, horsetails, club-mosses and their allies. In these organisms he demonstrated the existence of two markedly distinct phases in their life-cycles (Fig. 117). A fern, for instance, produced myriads of spores, each of which gave rise to a small, flat, green expansion or prothallus, usually not more than $\frac{1}{2}$-inch in diameter. On this structure arose two organs, one of which—the archegonium—contained an egg-cell or ovum, while the other—the antheridium—contained numerous very minute mobile fertilising cells or sperms. The product of fusion of the ovum and sperm—the "zygote" or yoked body—grew in due course into a new fern plant producing spores once more. These two phases, he found, alternated regularly, and this "alternation of generations" was demonstrated as universal throughout the whole of the higher cryptogams, although varying in detail in the different groups.

Hofmeister also traced the life histories of mosses and liverworts, and showed that alternation of generations occurred

amongst these forms also, but that in them the prothallus or sexual phase was the larger and more important, and that the asexual or spore stage was considerably reduced, and was, moreover, partially parasitic on the sexual.

Not content with these discoveries, Hofmeister proceeded to investigate the life histories of the pine and its allies, and showed that in these forms the sexual phase became more and more reduced, until, at last, for the sake of protection, it remained enclosed within the spore wall. The zygote or young embryo (Fig. 118, E) was not only embedded in the prothallus, P, and spore wall, SW, but, further it was hidden within the sporangium, SP, the whole surrounded by an accessory integument or testa, T, forming the "seed," the characteristic reproductive organ in all the higher plants or Spermatophyta.

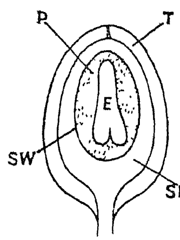


FIG. 118.—SEED.

Phylogeny.—These wide generalisations, linking up as they did the lower and higher plants, enabled botanists to realise that the key to the true understanding of the Flowering Plant lay among the hitherto despised and neglected Cryptogams. Published as they were about the time when the "Origin of Species" opened men's eyes to a new way of looking at organic nature, Hofmeister's researches helped materially to show that the connection between plants was phylogenetic or genealogical, and that linear classifications did not express their true relationships at all. The dogma of the constancy of species, which had been such an incubus on the shoulders of the taxonomists of the past, and which had driven them to all sorts of subterfuges to reconcile self-evident facts with preconceived ideas, slowly disappeared, and the plant world was visualised as a great tree whose roots were buried among the unicellular forms of the remotest past, while the tips of the loftiest twigs were the living plants of the present day.

Fossil Plants.—It will be remembered how Brongniart and others, earlier in the nineteenth century, did much to elucidate the structure of fossil plants, and came to the general conclusion that the oldest, Primary or Palæozoic, rocks, and

more especially the Coal Measures (p. 99), were characterised by the preponderance of ferns and fern-like types, and that seed-bearing forms did not appear until quite late in geological history. But in 1895 Williamson and Scott investigated a supposed fern stem which had been discovered some years previously in the coalfields of Lancashire, and found that it showed pronounced secondary thickening, like a modern larch or pine, a feature not possessed by any living fern, and yet that it had leaves like those of a fern. Further, in 1903, some of these leaves were found to bear seeds, quite like those of a cycad, an ally of the pine. Seed-bearing plants were thus seen to be enormously older than had previously been supposed, and after similar fossils from the Primary rocks, hitherto regarded as ferns, had been investigated, it became apparent that most of the vegetation of that far past epoch in the world's history did not belong to the fern alliance at all, but to an entirely new class of plants to which the very appropriate name of "Pteridosperms," or Seed-ferns, was given.

Cell Structure and Heredity.—We saw how, in 1838, Robert Brown discovered the nucleus in the cells of the orchid-leaf, and how, in the years that followed, its presence was found to be universal in all living cells (p. 203). After the birth of the Evolution Theory, in 1859, attention was more and more directed to the discovery of the methods by which the characters of the parents might be handed on to the offspring. It was obvious that the answer to the riddle lay in the germ cells (gametes), and as a germ cell deprived of its nucleus soon died, it was concluded that the nucleus must be the essential part, the one that primarily concerned heredity. The ovum had a relatively large nucleus, and the sperm, or what corresponded to it, was composed almost entirely of nuclear material. Investigators, armed with micro scopes of high magnifying power and skilled in the use of all the apparatus of the laboratory, examining growth-mechanism, discovered that every time any cell divided, its nucleus went through very remarkable changes, collectively called "mitosis," from the Greek word meaning "thread." The nucleus when at rest (Fig. 119, 1) was seen to consist of a very delicate membrane, M, enclosing a network, N, composed of a substance which had

a great affinity for certain aniline dyes, and which, for that reason, received the name "chromatin," the colourable matter, to contrast it with the less easily stainable ground substance in which it lay. When division took place the chromatin broke up into separate bodies called "chromosomes," or colour bodies, usually resembling short hairpins, and apparently of very complex structure. One remarkable fact soon came to light—viz., that the number of chromosomes was constant for any particular plant or animal, for the phenomena of mitosis were found to be fundamentally identical in the two kingdoms. Thus the number of chromosomes in the lily and in the salamander is twenty-four, and in the human being forty-eight. The chromosomes arrange themselves across the equator of the nucleus, which at the same time loses its membrane, and from this equatorial plane faint streaks of threads converge to either pole. The chromosomes next split lengthways (Fig. 119, 2 C), and presently each half retreats along the striæ to either pole (3 C′), where the fragments are reconstructed into daughter nuclei (4 N). A new wall is then laid down across the equator of the spindle (4 CW); so two new cells are constituted which then grow.

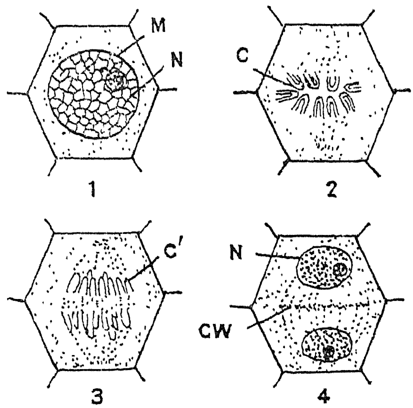


FIG. 119.—MITOSIS OF THE NUCLEUS.

With the germ cells the number of the chromosomes, which we shall call $2x$, is halved at some period in the life-cycle, before the formation of ovum and sperm. This halving is obviously obligatory, otherwise the number of the chromosomes would be doubled every time the fusion of an ovum and a sperm took place, leading to an impossible condition of affairs. Let us examine two examples of this phenomenon.

Alternation of Generations and Nuclear Division.—The nuclei of the cells of a typical fern at division contain $2x$

chromosomes, and this number is maintained up to the moment of the formation of the spores. The nucleus of the spore is found, however, to contain only x chromosomes, and all the cells of the prothallus to which the spore gives origin, including the ovum and the sperm, have the same half number. When ovum and sperm unite, the number of chromosomes in the nucleus of the resulting zygote is, of course, $2x$, and that number is adhered to in the cells of the embryo, seedling and adult, until spores are formed once more. By a curious modification of mitosis, called "meiosis" or reduction, the number of chromosomes is reduced to one-half in the parent cell of the spore. It will be apparent, therefore, that the very obvious alternation of generation in the fern life-cycle is accompanied by an equally regular though hidden alternation in nuclear conditions.

A very common seaweed, found on all rocky shores, is the "bladder-wrack," or Fucus. In this plant's life-cycle there is no alternation of generations, for there is no asexual stage at all. The nuclei of the body cells contain $2x$ chromosomes, but those of the ovum and sperm contain only x. The reduction in this case is effected at the moment of the formation of the gametes, so that the zygote regains the standard number $2x$. The condition in Fucus is that common to the whole animal kingdom, in which there is no such alternation of generations, as we have recognised to occur in the vast majority of the members of the plant world.

Gametes as Transmitters of Hereditary Characters.—From what has been said it would appear that biologists are justified in regarding the nuclei of the gametes as the essential organs concerned in the transmission of hereditary characters; indeed, no other means of transmission exists, but how that transmission is actually effected we do not know. It is a riddle that may be solved in the future, along with the equally mysterious problem how a minute particle of granular protoplasm has the power of nourishing itself, reproducing itself, and responding to stimuli from within and from without.

Modern Views on Evolution.—Although a fierce battle, lasting for many years, raged over Darwin's famous book, "The Origin of Species," adherents to the theory it propounded

increased in number, and, by the end of the century, the doctrine of "Evolution by Natural Selection" steadily gained ground, and made its influence felt in every department of human thought. All the same, even its strongest supporters, men like Huxley, Hooker, Lyell, had to admit that, while the general principle seemed unassailable, there were very many confusing problems awaiting solution. For instance, physicists of the standing of Lord Kelvin found themselves unable to concede anything like the number of years that, according to the biologist, would be necessary for the evolution of the million or more types of organism now existing on the earth's surface. It is true that the views of the physicists have changed very considerably during the past generation, and an earth capable of supporting life might, they now admit, have existed many millions of years ago; but as recently as 1876, Tait, professor of physics in Edinburgh University, and a co-worker with Kelvin, postulated only 15 millions of years for the age of the earth as a habitable globe even for the very simplest organisms. But when the span of the earth's life was extended to anything between 1,600 and 3,000 million years (p. 354), instead of the paltry 15 million that Tait would concede, the difficulty of time might be said to have been got over. But there were other difficulties.

No one can say how life originated on the globe (see p. 364), but it is certain that the earliest recognisable forms (the protista) were very primitive unicellular vegetable organisms, and it is equally certain that from these lowly beginnings, over a vast period of time covering something like 300 million years, higher forms were slowly evolved in two great divergent branches, the vegetable and animal kingdoms as we know them today. The actual cause of this wonderful evolution is still to some extent a controversial question, and though natural selection and sexual selection postulated by Darwin may be the prime instruments in the progressive change, it is now realised that this is not all the story.

Whatever may be the ultimate explanation, the broad facts of evolution are clear enough; they are revealed unmistakably in the unbroken and indelible record of fossiliferous rocks,

throughout the long range of geological time (see table on p. 483). It is in the oldest (pre-Cambrian) rocks that the beginnings of life must be sought, but here the fossil record is virtually blank, because simple soft-bodied unicellular organisms, the protista, like marine algæ and protozoa, flagellata, etc., could leave practically no permanent imprint, especially since these rocks have been often contorted and changed (metamorphosed) by heat agency. By the time the Cambrian rocks are reached, life is in full swing, and already of a relatively high (multicellular) order—invertebrates like molluscs, the worm family, and crustaceans (especially trilobites) are flourishing, but all aquatic and nothing higher in the scale of life. The record is more abundant in the succeeding Ordovician, while millions of years later, in the Silurian epoch, which lasted over 30 million years, the first beginnings of vertebrate (back-boned) life appear in the form of primitive fishes (elasmobranchs), with typical gills but with unsymmetrical so-called heterocercal tails (a long and short lobe as in sharks of today). In the succeeding (Devonian) epoch some new fish-like creatures (dipneusts) appear which, by living in mud that occasionally dried, had acquired the habit of utilising their swim-bladders as means of oxygenating their blood by gaseous exchange (air), instead of their now useless gills. These creatures had invented, so to speak, primitive lungs, and they were destined to usher in a new race of air-breathing animals, by emergence from their original homes (water) to land. In the next epoch, the long Carboniferous period, not only was the land conquered, but also the air, for now amphibians (like the frog tribe—still partly tied to their watery home) appear as well as insects, derived from lower worm-like forms by progressive evolution. Towards the end of the Carboniferous period, reptiles, derived from certain amphibian stocks, were beginning to appear.

Moreover, in multitudinous other directions progressive development was occurring, yielding a rich variety of new forms of life adapted to their slowly changing environment; also by now plant life had become air-breathing, and reached the comparatively advanced or complex forms of huge fern-like trees and giant horse-tails (see p. 424).

From the point of view of human and mammal ancestry, however, amphibians were the most important living forms of the long Carboniferous epoch. They had developed four legs with five-fingered toes, from certain cartilaginous bones of the fins of their fish ancestors, and this endowed these creatures with the mobility requisite for existence on land. These limbs and toes and their entire skeletal framework have been retained by many of their descendant races, including mammals, to which they gave rise, though lost by disuse in serpents or modified as in the case of birds. Their immediate descendants, the reptiles, which were very varied and abundant some 20 million years later in the Permian epoch, had emancipated themselves entirely from the water, so far as breathing was concerned, by elaboration of proper lungs; and during the succeeding Triassic and Jurassic epochs they became the masters of the earth. Enormous monster reptiles, like dinosaurs, roaming over the land, made life very precarious for any other types of animal. Nevertheless, during the late Triassic period primitive mammals began to appear, small and tentative in type, evolved from smaller reptilian stocks, and still endowed with certain reptilian qualities, such as hatching their young from eggs laid outside the body. Pouched mammals (marsupials) like small kangaroos followed, and about the end of the Jurassic period, when the great reptiles had become extinct, true mammals began to appear (placentals), descended from some primitive pro-marsupial stock. The young were now born after a definite period of gestation within the uterus of the mother, and were sustained in their early infancy by milk sucked from their mothers' mammæ.

But in the Cretaceous age, which succeeded the Jurassic, these mammals were still only small and very primitive, living principally upon insects. Yet from this primitive stock, by an elaborate process of branching, all the multifarious mammal forms known today have descended—carnivora like lions, tigers, wolves, etc.; herbivora like cows, sheep, horses, etc.; rodents, bats, monkeys, etc. One of the representatives of this early stock took to an arboreal life, apparently for reasons of safety, and this new departure led to tremendous

consequences. For it led to a great development of their grasping five-fingered fore-limbs, and to a greater use of their eyes, instead of the sense of smell, which was the principal sense used by other pro-mammals and mammals in scenting food, danger, etc. The descendants of this arboreal stock became tarsoids and lemurs, and from the tarsoids monkey-forms (primates) gradually evolved. This took place apparently in the Eocene period, and in the succeeding Oligocene already two great branches of primates had diverged—(1) the platyrrhine or true monkeys of the American continent, and (2) small catarrhine or anthropoid apes of the old world. As Darwin foreshadowed, it was from the latter stock (now comprising the gorilla, chimpanzee, orang, and gibbon) that the human stem eventually branched off in Miocene times, only about 2 million years ago.

No one, of course, believes that this human stock has descended from existing anthropoid apes; the truth is rather that it and the existing apes have all branched off from some arboreal ancestral form, which was the common progenitor of the entire group, in the same kind of way that worm-like forms were the common progenitors of molluscs, crustaceans, and fishes in Cambrian or Silurian times.

All the old forms in the geological record are now extinct as actual species, and the existing species of all plants and animals must be looked upon as modern representatives, more or less changed, of the older forms which once flourished and were no doubt well adapted to their environment; so that in the gigantic tree of life, which has been growing for over 300 million years, we only see now, as it were, the terminal twigs.

But the main branches of this great tree, with most of its sub-branches, can be clearly discerned in the geological record, and the recognition of this marvellous evolutionary development has finally disposed of the old dogma of constancy of species.

If confirmation of the facts of evolution were required, they are to be found on every hand in the study of comparative anatomy, by which the homology of bony or other parts coincides with the closeness of genetic relationship; it is to be found in the existence of tell-tale vestigial and rudimentary

parts no longer of any use, because the organism has changed its mode of life, but betraying clearly its past (phylogenetic) history; and it is to be found in the mode of individual (ontogenetic) development of the young, for example, of mammals, from the fertilised ovum, where the embryo more or less faithfully recapitulates the history of its ancestors by passing successively through a fish-like and amphibian-like development. No rational interpretation is possible except that of evolution to explain the multitudinous facts of biology; in the light of this simple explanation, all the lines of evidence converge to a single focus and living Nature becomes intelligible.

Evolution does not mean that change is necessarily progressive; in point of fact, it has been for the most part progressive; from the more simple to the more complex, from the lower to the higher. But it is not necessarily so; some species have practically stood still for millions of years, others, by changing their mode of life, have lost the use of organs (eyes, for example) once useful. Man himself has largely lost his sense of smell, and has by no means the range of vision that some lower animals have. Many forms have definitely retrograded by adopting parasitic habits, like intestinal worms, and evolution, *so far as we know*, is not guided by any conscious agency of design; it operates by fitting an organism to its surroundings and enabling it to live and breed. And though it is universally recognised that natural selection (*i.e.*, elimination of the unfit) has played an enormous part, it would seem that geographical changes leading to isolation and prevention of interbreeding must also have had a great deal to do with the inception of new species leading to fresh branches. Neither of these causes, however, could operate without something to work upon, some definite advantage in relation to the environment that could be selected by Nature. Variation or mutation, a tendency which individuals sometimes show to depart from the average, seems to supply the clue, because any change, however small, which gave such individuals an advantage in the struggle for existence would lead to their increase at the expense of normal individuals; and it is probable that Cosmic rays (p. 269) have played a part in initiating such variation.

Darwin regarded infinitesimally small variations in the organism as slowly accumulating from generation to generation, handed on by heredity; but the problem was: Of what possible value could these extremely slight changes be to the plant or animal in their initial stages? Some experiments carried out by Professor De Vries of Amsterdam in 1901, seemed to suggest that new varieties, termed by him "mutations," might spring into existence at a bound, so to speak, and hence that the creation of new species might take place much more rapidly than was generally supposed or assumed by the Darwinian theory.

A far more serious criticism was advanced in 1885 by Weismann, professor of zoology in Freiburg. He denied the inheritance by the offspring of any characters acquired by the parent during its lifetime. This was striking at the very root of the Darwinian theory, although Weismann proclaimed himself to be a confirmed evolutionist. His thesis was that a certain part of the fertilised ovum, both in the plant and in the animal, is, so to speak, set aside from the very beginning as the starting-point for the germ cells of the new organism, and to this hypothetical substance he gave the name of "germplasm," to distinguish it from "somatoplasm," which was concerned solely with the formation of the body or soma. If the germplasm was alone responsible for inheritance, it was obvious that modifications of the somatoplasm could not be transmitted, and that any structural feature induced by use or disuse, or by nutritive or environmental influences generally, never affected the germplasm in such a way as to cause the offspring to exhibit the modification the parent had acquired.

Although there were many converts to Weismann's doctrine, it was apparent that there was no evidence to show that the germ cells were actually stable and lived a life altogether apart from the rest of the body, shielded from the influences affecting the organism as a whole, while positive evidence of the inheritance of acquired characters was rapidly accumulating—such as, for example, certain cases described by Kammerer in 1925.

In 1900 a new name burst upon the biological world that is now familiar to every student of the science—the name of Mendel. Gregor Johann Mendel was born in Moravia, and, in 1843,

entered the Augustine seminary of Altbrünn, subsequently proceeding to the University of Vienna, where he studied science. In 1853 he returned to Brünn as a teacher, and finally became abbot of the monastery, where he remained till his death in 1884. During the long quiet years of his residence at Brünn he took a keen interest in the local scientific society and published several papers in its journal, dealing with the experiments he had carried out in the monastery garden on the hybridisation of peas and hawkweeds, an account of which he gave in 1865. Whether it was because biologists did not attach any particular

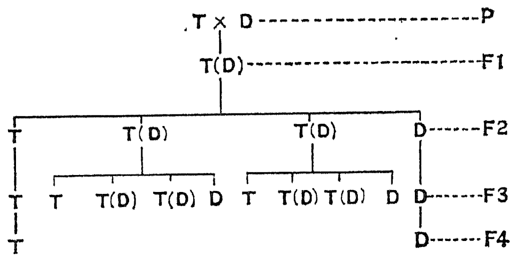


FIG. 120.—MENDEL'S LAW OF INHERITANCE (PUNNETT).

importance to the abbot's work, or because the paper was hidden away in an obscure journal, the fact remains that these now classic experiments, and the epoch-making conclusions to be drawn from them, lay unknown for thirty-five years until the paper was discovered in 1900, and immediately attracted the attention of the whole biological world. Let us see what Mendel discovered and what conclusions may be drawn from his observations.

Mendel's Law of Inheritance.—The ordinary garden pea in cultivation shows a number of distinct strains or breeds. Some forms are tall, some are dwarf, some red-flowered, some white, some have wrinkled seeds, others smooth, and so on, and each strain, if self-fertilised, "breeds true." In one set of experiments Mendel artificially crossed a tall strain with a dwarf (Fig. 120, T×D), and obtained a progeny, F_1, all of which were tall, no dwarfs and no intermediates appearing. Apparently in this first filial generation tallness overpowered dwarfness (indicated in the figure by placing D within brackets), and

hence, Mendel said, tallness in this case was "dominant" and dwarfness subsidiary, or "recessive." He then cultivated all the seeds resulting from the self-fertilisation of these tall hybrids, but instead of getting a second generation, F_2, of tall plants, he got a mixture of tall and dwarf, without intermediates, the tall plants being three times as numerous as the dwarf. He next self-fertilised all the offspring of this second generation (F_2) and cultivated their seeds in turn, and found that the seeds of the dwarf plants, D, developed into dwarf plants and continued to breed true in subsequent generations. He found, however, that only one-third of the tall plants—viz., T—continued to breed true, and that the other two-thirds, T(D), behaved exactly in the same way as the tall plants of the first generation, (F_1)—viz., producing three tall to one dwarf.

Expressed numerically, in the second generation, out of every 100 plants, 75 were tall and 25 were dwarf, and out of the 75 tall, 25 bred true, so that the final result was 25 tall breeding true, 25 dwarf breeding true, and 50 tall breeding tall and dwarf in the same proportions as those of the first generation. Mendel found that this law held good for every pair of characters that he selected, each pair of characters being entirely independent of every other pair.

Mendel now proceeded to formulate a "theoretical interpretation of this scheme, which he realised must be in terms of germ cells. He conceived of the gametes as bearers of something capable of giving rise to the characters of the plant, but he regarded any individual gamete as being able to carry one, and one only, of an alternative pair of characters. A given gamete could carry tallness or dwarfness, but not both."

In an admirable sketch of "Mendelism" Professor Punnett of Cambridge summarises the effect of Mendel's discoveries. He points out that hereditable variation is based in the gamete and not in the individual. Somewhere in the course of the production of the gamete there is added or removed the factor to which the new variation owes its existence. It appears as a sudden step, and not by gradual and almost imperceptible augmentation. Once formed its survival is determined by

natural selection; if of value in the struggle for existence it will be preserved, if harmful it will be eliminated, but if neither useful nor harmful, there seems no reason why it should not persist.

On the old view no new character could be developed save by piling up minute variations; but many characters exist whose utility cannot be explained or accounted for. On the newer view this difficulty is got over, for, provided the new variation is not directly harmful, it may persist, and thus we do not require to seek for a utilitarian motive behind all the multitudinous characters of living organisms. The function of natural selection is thus selection, not creation; it does not produce the new variation, it only determines whether it shall or shall not persist.

It is worth noting that Mendel's work was published only five years after the "Origin of Species" had left the printer's hands, yet Mendel makes no reference to Darwin's work, and similarly, "it is remarkable that, as far as one knows, Darwin never in any way came across Mendel's work" (Seward).

Problems in Metabolism.—The problems connected with nutrition and the nature of the vital processes, in plants and animals, received much attention during the latter half of the nineteenth century. The most important of these problems lay in the fields of constructive metabolism, problems that cannot be said to be solved even today, although progress has undoubtedly been made towards their solution. Let us first briefly review the general situation.

The animal and plant alike are capable of feeding themselves, and maintaining life by absorbing and digesting materials from without, but these materials differ very markedly in the two cases. The animal depends on a supply of complex organic food substances, which may be grouped as proteins, carbohydrates and fats. These complex bodies represent stores of potential energy which become kinetic in the organism, by the oxidation of their constituents, due to the process of respiration. They form the fuel that, on combustion, keeps the engine going. The seat of these activities is the mysterious substance proto-

plasm, which was identified as common to plants and animals about the middle of the nineteenth century—"the physical basis of life," as Huxley called it. Plant protoplasm also has to be supplied with complex food materials of a similar nature, but in the great majority of plants, what is taken in, from the environment, is inorganic—viz., water and soluble salts, derived from the soil, and carbon dioxide gas from the air, the former absorbed by the root and the gas by the leaf. It cannot be too strongly emphasised that these inorganic substances do not form the "food of plants"—a phrase so frequently met with in elementary textbooks of botany. Since these substances are already fully oxidised, it is manifest that they cannot be used as fuel; thus they contain no available stores of energy, and therefore are of no service to the plant protoplasm. The plant has thus a preliminary task to perform from which the animal is exempt—viz., to manufacture proteins, carbohydrates and fats required, not only for its own protoplasm, but, in the long run, for that (as food) of the animal also. It should be noted that the three great groups of organic compounds comprised in the generic terms, proteins, carbohydrates and fats, are the essential basis of all living material. They are very complex in their chemical constitution. (1) *Proteins* (proteids) are complicated compounds of colloidal nature, built up chemically by the linking together of numerous units called amino-acids, of which the simplest is glycine or glycocoll—amino-acetic acid, $NH_2 \cdot CH_2 \cdot COOH$. Proteins therefore contain nitrogen as well as carbon, hydrogen, and oxygen, and some of them contain phosphorus and sulphur as well. (2) *Carbohydrates* are complex compounds of carbon, hydrogen and oxygen, in which the two latter elements are present in the ratio of two atoms of H to one of O. The simplest carbohydrates are the sugars, like grape sugar (dextrose or glucose), $C_6H_{12}O_6$, and cane sugar, $C_{12}H_{22}O_{11}$, but many natural carbohydrates are very complex in structure, like starch and cellulose. (3) *Fats*, like carbohydrates, contain only carbon, hydrogen and oxygen, but they are built up on an entirely different type of structure. They are all derivatives of the well-known compound of alcoholic type, glycerol, $CH_2(OH) \cdot CH(OH) \cdot CH_2(OH)$

(glycerine), combined with long-chain fatty acids (palmitic acid, stearic acid, oleic acid, etc.), in such a way that water is eliminated by *condensation* (one molecule of a fat being formed from three molecules of fatty acids and one of glycerol, by eliminating three molecules of water). When fats are treated with water in an appropriate way they break down into these components (glycerol and fatty acids) by the process of fission, called *hydrolysis* as we have seen (p. 399). Soaps are the sodium salts of these fatty acids.

In the plant the "autotrophic" synthesis of proteins, carbohydrates and fats is in some mysterious way associated with the green pigment chlorophyll, so characteristic of the plant world; for ordinary non-green plants (fungi, etc.) are dependent on organic food supplies, as animals are, and are equally incapable

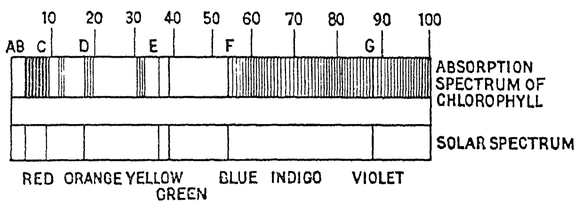


FIG. 21.—ABSORPTION SPECTRUM OF CHLOROPHYLL.

of creating them. The continuance of life on the globe obviously, therefore, depends ultimately on the activities of the green plant. Biologists at the end of the eighteenth century regarded the vegetable kingdom as subordinate to the animal, while the truth lies in precisely the opposite direction—without the green plant the animal could not exist.

Photosynthesis.—What, then, is this all-essential green pigment, and how does it operate? It may be remembered that Grew (p. 66) was the first to isolate it from the leaf by the aid of olive oil, and that Priestley and Ingenhousz (p. 206) noted that, when exposed to sunlight, oxygen was given off from plants containing it. In 1819 two French chemists, Peletier and Caventou, called the pigment "chlorophyll"—literally "leaf green"—a name by which it is now universally known. Two questions then arose, first, what was the substance,

and, second, what was its relation to sunlight? for, without sunlight, the chlorophyll was apparently powerless.

The first step of importance was taken by Sir David Brewster, who found that an alcoholic solution of chlorophyll gave a very pronounced absorption spectrum (Fig. 121), showing a dark band in the red region, and almost complete obliteration of all the violet and most of the blue, with less marked bands in the orange and green. In 1864 Sir Gabriel Stokes found that chlorophyll was a mixture of two green and two yellow pigments, a discovery which was confirmed and extended by Willstätter in 1913. The pigments are (1), α-chlorophyll, (2) a green to yellow-green one, β-chlorophyll, (3) an orange-red pigment, carotin, and (4) a yellow one, xanthophyll. One curious point emerged from Willstätter's work—viz., that magnesium was the only metal present, although iron had for long been regarded as a constituent of the pigment, because leaves could not be induced to become green unless a trace of an iron salt was present in the soil in which the plant was grown.

The importance of Willstätter's work lay in the fact that it showed a close chemical relationship between chlorophyll (α and β) and hæmatin the basis of hæmoglobin in the red blood of animals, whose function is that of an oxygen carrier to animal cells. Although there is so much difference in appearance and function, both types of molecule are built up on a similar atomic framework. This framework is a system of rings, each containing four carbon atoms and one nitrogen atom, and so these bodies belong to the heterocyclic series (p. 394). And though the atomic side-chain appendages to these rings may differ in the two cases, the skeletal atom-linking is similar, with this important difference, that the nitrogen atoms of the ring systems are linked together by an intermediary magnesium atom in the case of chlorophyll, but by an iron atom in the case of hæmoglobin. It is to the presence of iron in the latter that its peculiar behaviour with oxgyen is due. Though as yet incompletely understood, we can say that in hæmoglobin the iron atom enables a whole molecule of oxygen to be taken up without the usual oxidation, which normally occurs when organic compounds take up oxygen. The oxygen

is instead loosely linked on to the hæmoglobin molecule, ready to be given up to "acceptor" substances in cells, such substances being themselves oxidised, while the "oxy-hæmoglobin" acts merely as carrier or oxidising agent (p. 395), and reverts to hæmoglobin after parting with its loosely-added oxygen.

This action is, of course, of enormous importance to all animals possessing blood. We owe a debt of gratitude to the worms, who were the first animals apparently in the evolutionary sequence to "invent" hæmoglobin; for it is the easy but necessary oxidation throughout their tissues that enables higher animals to secure the requisite energy for their complex life-processes; and this could hardly have been done without a mobile carrier. When the blood passes through the lungs of a higher animal, the hæmoglobin contained in its red corpuscles picks up molecular oxygen from the air breathed in, and so the resulting "oxy-hæmoglobin" of the arterial blood circulating to all parts of the body effectively passes on this oxygen to the cells to do its important work, before returning as venous blood, deprived of its surplus oxygen, to the heart and lungs (p. 61).

Chlorophyll in plants exercises a quite different function. It does not circulate, but remains in one place, say in the chloroplasts of the leaves, to convert CO_2 and water into carbohydrates through the agency of light—that is to say, to transform solar energy into chemical energy. And when the matter is considered closely, it is seen that chlorophyll does this by a process of *reduction* (of CO_2), whilst hæmoglobin effects the easy release of such stored energy by *oxidation* (to CO_2).

About the same time that Stokes was elucidating the nature of chlorophyll, Sachs, professor of botany in Würzburg, was carrying out research on the first organic product formed in the leaf as the result of the activities of chlorophyll in presence of sunlight, and made it out to be starch. He showed that starch disappeared from the leaf at night and reappeared by day; and, by growing plants under variously coloured solutions enclosed in double-walled bell-jars, he came to the conclusion that the production of this carbohydrate took place most vigorously when the leaves were exposed to the yellow-red rays of sunlight. It soon became apparent that starch, a very

complex organic compound, could not be the first product of "photosynthesis," as the process came to be called; and later research indicates that cane sugar is the first recognisable product. Now cane sugar, $C_{12}H_{22}O_{11}$, can be synthetically formed from a mixture of glucose and fructose (fruit sugar), both isomers, $C_6H_{12}O_6$, by eliminating a molecule of water (*condensation*); whilst starch is produced by the plant from glucose alone by condensation. In 1870, von Baeyer, professor of organic chemistry in Munich and afterwards in Berlin, put forward a theory which has not yet been superseded. It had been shown, ten years previously, that a substance having some of the properties of sugar could be obtained from formaldehyde, CH_2O, now well known in the preservative having the name of "formalin"—viz., by treating it with an alkali. Working on this basis, Baeyer suggested that the leaf, when exposed to radiant energy, seized, as it were, upon a molecule of carbon dioxide from the air and "reduced" it—*i.e.*, removed oxygen—in presence of a molecule of water, to formaldehyde, oxygen being thus formed as a by-product, as Priestley and Ingenhousz had observed a century before. This photo-chemical change is induced in some way by the agency of the chlorophyll, functioning as transformer of solar energy into the chemical energy requisite for the change. Formaldehyde is one of those substances which chemists call polymerisable, that is to say, one which has a great tendency to combine with itself, yielding complex compounds by polymerisation. Thus six molecules of formaldehyde could form the sugar called glucose or "dextrose." This sugar when deprived of water by condensation could then become starch. The series of reactions may be represented approximately by the following equations:—

$$\underset{\text{(carbon dioxide)}}{CO_2} + \underset{\text{(water)}}{H_2O} = \underset{\text{(formaldehyde)}}{CH_2O} + \underset{\text{(oxygen)}}{O_2} \qquad \underset{\text{(reduction)}}{\text{1st stage.}}$$

$$\underset{\text{(6 mols. formaldehyde)}}{6\,CH_2O} = \underset{\text{(1 mol. glucose)}}{C_6H_{12}O_6} \qquad \underset{\text{(polymerisation)}}{\text{2nd stage.}}$$

$$\underset{\substack{\text{(large number of}\\ \text{glucose molecules)}}}{nC_6H_{12}O_6} = \underset{\substack{\text{(one large molecule—}\\ \text{starch or cellulose)}}}{(C_6H_{10}O_5)_n} + nH_2O \qquad \underset{\text{(condensation)}}{\text{3rd stage.}}$$

The reason why the starch disappeared in the dark can be explained by saying that it was reconverted into sugar, and transferred to other parts of the plant to supply nutritive needs, the constructive process being then in abeyance.

Baeyer's theory of photosynthesis, which has been amplified in recent years, is probably not far from the truth, but it affords only the merest glimpse of the mechanism, underlying the multifarious synthetic processes occurring in Nature's great laboratory. Starch and cellulose, the chief carbohydrates of the plant world, are still more or less inscrutable photosynthetic mysteries.

The closely related problem, as to which of the solar rays were most effective in photosynthesis, occupied the attention of many investigators towards the close of the century, more especially Professor Pfeffer of Leipzig and Professor Timiriazeff of Moscow. The former held that the most efficient region of the spectrum lay in the yellow, and that the maximum of photosynthesis coincided with the maximum of illumination; the latter asserted that the really efficient rays were those in the neighbourhood of Fraunhofer's lines B and C (Fig. 121). Timiriazeff's view seemed to receive support from the researches of Engelmann, who, in 1884, hit upon a very ingenious method of determining the position of the constructive rays. It was well known that certain bacteria were exceedingly sensitive to minute traces of oxygen gas, and collect round any spot where that gas is being produced. Engelmann argued that if such bacteria were introduced into water in which a filamentous green alga lay, and if the filament were illuminated by the solar spectrum, the bacteria ought to congregate wherever oxygen was being given off—*i.e.*, wherever photosynthesis was taking place. On testing his method he found that the bacteria swarmed chiefly round the spectrum lines B and C, as Timiriazeff asserted, but also to a less extent in the blue region near Fraunhofer's line, F, indicating that these were the waves of radiant energy that were chiefly responsible for the elimination of oxygen, and therefore, presumably, for photosynthesis.

More recent research work by Baly, Heilbron, and Barker

has reopened the whole question, and these workers have transformed carbon dioxide into formaldehyde and sugar by means of light in presence of nickel carbonate; but the problem is not solved even yet. As Timiriazeff wittily expressed it in the Croonian Lecture in 1903, we must be content for a little while longer to contemplate green leaves locked up in glass bottles, like the philosophers in "Gulliver's Travels," who, with the aid of similar apparatus, taught their pupils how to extract sunbeams from green cucumbers!

The Importance of Carbohydrates.—The most remarkable point in the whole photosynthetic story is that, although the element carbon constitutes about one-half of the dry weight of any plant, the whole of this element is obtained from the quite trifling quantity of carbon dioxide in the air—viz., 3 to 4 parts in 10,000.

The space we have given to this subject is not excessive when we realise its transcendent importance to the human race. Were it possible to collect all the carbohydrates that form the most substantial part of our daily food, we should find that they amounted to about 15 ounces for each individual. Most of this comes from cereals, of which wheat is the chief. Chemical analysis of wheat shows it to consist of about 70 per cent. of starch and sugar, 12 per cent. of nitrogenous material, 2 per cent. fats, 2 per cent. of minerals and 14 per cent. of water and indigestible substances. The value of food to us depends primarily on the energy it yields on oxidation (p. 448), and if we adopt the "calorie" as our unit of measurement (*i.e.*, the amount of heat required to raise a kilogram of water from 0° C. to 1° C.), we find that 1 pound of wheat yields about 1,600 calories. It has been calculated that an average man doing moderate physical labour requires about 3,000 calories per day, so that, were wheat his only source of nourishment, he must be supplied with at least 2 pounds of that cereal in the twenty-four hours, or 730 pounds per annum. Of course, "man does not live by bread alone"; he requires other substances as well, in which wheat is deficient.

The world's wheat crop for 1924-25 was between 140 and 150 million tons, so that this harvest could support approxi-

mately 450 million persons. When we add the combined amounts of other grain and root crops, there is no difficulty in seeing whence the carbohydrates come, that form the daily bread of the world's population. And yet all this vast food supply is manufactured by the green plant from carbon dioxide in the air and dilute soil-solution, provided there is sunlight, whence the plant derives its energy. We need not wonder that the ancient Egyptians deified the sun as Ammon-Ra—"the giver of life." Perhaps the day may not be far distant when chemists and biologists will discover how to manufacture carbohydrates without the green plant's assistance, but that day has not yet dawned.

The attempted Synthesis of Proteins.—If the molecular structure of such relatively simple materials as cellulose and starch be thus shrouded in mystery, what is to be said of the still more complex proteins, which form the fundamental basis of protoplasm itself? The difficulties connected with this line of research did not deter men like Emil Fischer from tackling the subject. He was able to show that both animal and plant proteins, on submitting to the mode of fission, called hydrolysis (p. 397), could be split up into substances called amino-acids, water being taken up chemically in this (hydrolytic) change. An amino-acid (p. 436) contains the group of carbon, oxygen and hydrogen atoms called "carboxyl," COOH (p. 390), along with another group, of nitrogen and hydrogen atoms, NH_2. If these two groups are linked by removing a molecule of water, we get CO−NH, which chemists call a "peptide linkage." The various amino-acids are constituted out of one or more NH_2 groups united with carbon chains carrying carboxyl, and Fischer was able in his laboratory to link a large number together giving "polypeptides," bodies which are regarded as probable stages in the construction of the molecules of proteins. To follow the line of investigation any further would plunge us in depths of organic chemistry which would only bewilder the reader.

Enzymes and Fermentation.—The three essential groups of substances involved in the growth and nutrition of both vegetable and animal protoplasm are, as we have seen, proteins,

carbohydrates and fats, but to render these available for immediate assimilation by, or incorporation in, the protoplasmic complex, they must be chemically transformed so as to enable them to be fitted into their appropriate niches in the molecular architecture of the animal or plant body. This chemical transformation, in its mode, is utterly unlike the manifold processes of the chemical laboratory, but it (*i.e.*, metabolism) is rather akin to fermentation.

The manufacture of wine and other alcoholic liquors had for centuries been regarded as a chemical process called "fermentation," and, indeed, metabolism in both plants and animals was somewhat vaguely ascribed to fermentative action. Little was known of these transformations until the middle of the nineteenth century, when Pasteur gathered together all the available data on the subject, and classified the ferments in two groups, "organised" and "unorganised." According to him, organised ferments were in all cases living organisms—bacteria, yeasts and other microfungi—and he held that fermentable processes were always due to their growth and multiplication; unorganised ferments, on the other hand, were colloidal organic compounds secreted by plant and animal cells, each such ferment adapted to a specific purpose, but capable of extraction from the living body and of operating apart from it.

During the years 1830-35 several unorganised ferments had been isolated, such as ptyalin from the saliva, which had the power of transforming insoluble starch into soluble sugar, equally in a test-tube as in the animal, diastase, which performed a similar duty in the plant, and pepsin, which dissolved proteins, breaking them down into soluble peptones, and so on. Later it was discovered that colloidal platinum—*i.e.*, platinum in a very fine state of suspension in water—had somewhat similar powers; and, finally, in 1896, Buchner succeeded in crushing yeast cells under a hydraulic press and obtaining from the product an extract-filtrate containing no yeast cells, but which was yet capable of fermenting glucose—*i.e.*, dextrose or grape sugar—into alcohol as efficiently as the living yeast itself. It thus came to be held that Pasteur's

classification was not strictly scientific, and that ferments were probably in all cases non-living, whilst the so-called "organised" ferments were minute organisms from which the real ferments, contained in their cell-sap, had merely not been isolated.

The term now generally applied to all such unorganised ferments is "enzyme," a word derived from the Greek *zyme*—meaning "leaven." From this leaven (yeast) the unorganised ferment had been extracted by Buchner. Many enzymes are now known and they are given names, ending in the suffix -ase, while the substance which they decompose (ferment) is generally known as the substrate.

Enzymes have certain remarkable characteristics. They are *specific* rather than general catalysts. Thus cane-sugar is transformed into glucose and fructose by the *specific* enzyme, invertase, discovered by the chemist Liebig in 1870; indeed one of their most remarkable features is their specific behaviour in relation to substrates. In order to make this more clear it is necessary to refer to a property exhibited by certain organic compounds, especially those of bio-chemical origin, known as "optical activity." The latter is the power which these compounds possess of twisting or rotating the plane of polarised light (p. 116), when a beam of such light is passed through them or their solutions. The instrument used for detecting and measuring this rotation is known as a Polarimeter. It has been found that such substances can each appear in two forms, of exactly opposite but equal rotation, that is to say one form of the compound rotates the plane to the right (dextro-rotatory) and the other an equal amount to the left (lævo-rotatory). For example, two such forms of lactic acid, $CH_3 \cdot CH(OH) \cdot COOH$, are known, one called *d*-lactic acid and the other *l*-lactic acid. It was le Bel and van't Hoff who first formulated a theory explaining such optical isomerism. Ordinary isomerism, which is a well-known phenomenon among organic compounds, is the appearance of two or more compounds (different) having the same percentage composition and empiric formula (p. 390), but different structural or constitutional formulæ (different mode of atom linking). The case, however, is

otherwise with optical isomerism, where the pair of isomers actually have the same chemical and physical properties as well as the same structure, but differ optically. The key to the riddle was found in 1874, by le Bel and van't Hoff, to lie in molecular asymmetry due to the presence of one or more asymmetric carbon atoms—*i.e.*, atoms linked by all four valencies to four *different* atoms or groups. The tetrahedral arrangement of these four atoms or groups (see p. 389) might be in a left-handed or in a right-handed order, differing much in the same way as a right hand does from a left, or a right-handed spiral from a left. This new kind of isomerism, due to differences in the arrangement of the same atoms in space, came as a shock to chemists and was at first ridiculed by men like Kolbe. But it is now well recognised and comes within the domain of a special branch, known as stereo-chemistry or the chemistry of space. Substances which do not contain an asymmetric carbon atom, like water, alcohol, acetic acid, benzene, etc., do not appear as space-isomers (stereo-isomers) and do not affect the plane of polarised light—they are optically inactive. On the other hand, the majority of organic compounds associated with life are asymmetric in their molecular build and optically active—they may appear in two forms related to each other as a right hand is to its image in a mirror (left hand), though in many cases only one form is actually known. And one of the most salient features about enzymes is that, when they are able to ferment an optically active substance, they can, as a rule, only act upon the one form and not the image-isomer, in much the same way, to use a simile of Emil Fischer, as an asymmetric key will only fit its own (asymmetric) lock. Where, as is generally the case with bio-chemical compounds, like carbohydrates and proteins, there are several asymmetric carbon atoms in the molecules the case becomes exceedingly complex, but Emil Fischer has largely unravelled this complexity for carbohydrates and to a less degree for protein derivatives.

Cane sugar is dextro-rotatory, but on hydrolysis (p. 397) it is decomposed, by the assimilation of a molecule of water, giving a mixture of two isomeric sugars, $C_6H_{12}O_6$, one glucose, dextro-rotatory, and the other fructose, which is not a space-isomer

and which is lævo-rotatory, but to a greater degree than glucose is dextro-rotatory. The mixture is therefore lævo-rotatory, and since the sign of rotation has been changed or inverted, the change is often called "inversion." The inversion by invertase (p. 445) is represented by the equation:

$$C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6.$$

It may also be brought about by boiling cane-sugar solution in the laboratory, with a trace of an acid. It is important to note that the acid does not combine chemically with the sugar, nor is it altered or destroyed in the process; the H-ions merely stimulate and accelerate the hydrolysis (*i.e.*, water-split) of the cane-sugar. This is another example of a catalytic action (catalysis), a *catalyst* being (see p. 396) an agent which, like H-ions, increases the velocity of change, but remains unchanged itself, in the succeeding reaction. And this is exactly what enzymes do. Like invertase in the cane-sugar split, enzymes increase enormously the velocity of chemical changes such as hydrolysis, oxidation, etc., which in their absence are indefinitely slow.

Yet, although these enzymes are non-living catalysts and may be preserved apart from the organism for indefinite periods, they are susceptible to heat, being rendered ineffective by temperatures only slightly above those of the living organisms producing them, when apparently the delicate complex is destroyed.

Like many other reversible catalytic reactions, known to Chemistry, fermentative action when it has proceeded for some time finally ceases, although the enzyme is still unaltered, and although there may be abundance of the fermentable substance still unacted upon. In short, the activity of an enzyme is retarded and finally stopped by the accumulation of the products to which it has given rise. If these products be simultaneously removed, the action proceeds until all the fermentable substance has disappeared (compare p. 399).

Very many enzymes have now been extracted both from plants and from animals, and are usually classified into five groups—viz.: (1) those which attack starches, or "amylases"; (2) those which decompose cellulose, "cytases"; (3) those which hydrolyse sugars, "invertase," etc.; (4) "lipases," which split fats, transforming them into glycerine and the corresponding

fatty acids; and (5) "proteases," which split proteins, breaking them down into amino-acids. The whole subject of enzyme action is one of great difficulty; much work has been done on them, including the recent researches of Willstätter; and various theories have been put forward to explain how an enzyme works, but their chemical nature is still obscure.

Carbohydrates in Physiology.—In the raw condition, starch appears as insoluble microscopic granules of organised structure, and when heated with water, these granules burst, giving a colloidal mixture (starch paste) of two kinds of particles, known respectively as starch cellulose and starch granulose. As these are digestible, whilst the raw granules are practically indigestible by human beings, this change on heating is of importance in the cooking of all starchy foods. The precise chemistry of starch is not yet completely understood, but it is certain that starch consists of complex molecules, of high molecular weight, derived in some way by the condensation (p. 440) of simpler molecules of grape sugar. And when starch is digested as food, the reverse changes occur (hydrolysis), leading finally to grape sugar. The first stage in the hydrolysis occurs in the mouth under the influence of the enzyme present in saliva, which causes the formation of maltose (a sugar which si soluble and isomeric with cane sugar); and eventually under the influence of other enzymes in the alimentary tract, the starch or maltose is converted entirely into grape sugar (glucose). Cane sugar, when taken as food, is similarly hydrolysed under the influence of enzymes, but it yields, as we have seen (p. 447), fructose as well as glucose. Both these sugars pass through the alimentary canal into the blood stream, where they are eventually oxidised to carbon dioxide and water (except in the case of the serious disease diabetes, where the sugar accumulates in the blood). The glucose derived from foodstuffs is, however, mostly not directly oxidised, but stored up in the system (muscles and liver) in the form of an insoluble reserve, very similar in properties to starch itself, and known as animal starch or glycogen.

These reserves of carbohydrate (glycogen) play a great part in animal economy: they serve to prevent excess accumu-

lation of glucose in the blood (glycosuria) and act as a barrier against temporary starvation. Moreover, glycogen is the direct agent in all muscular activity. The chemistry of this wonderful action is not yet understood; but Professor A. V. Hill has recently shown that muscle contraction (the basis of all animal movements) brings about the conversion of glycogen into *d*-lactic acid (p. 445) with such extreme rapidity as to simulate an explosion, and that when the muscle relaxes, this lactic acid is neutralised by the sodium bicarbonate of the blood, giving CO_2. There is nothing like this known among the familiar reactions of chemistry, nor like the reverse change that rapidly occurs, by which a portion of the lactic acid is reconverted into glycogen. This reverse reaction cannot occur in absence of oxygen, and the function of the oxygen is to burn up (oxidise) about a sixth of the lactic acid, so providing the chemical energy by which the remainder is converted into glycogen.

In absence of oxygen or of sodium bicarbonate, or if the muscular exertion is too rapid for the reverse changes to occur, lactic acid accumulates, and this is the cause of fatigue. On the other hand, it is the lactic acid which, by providing hydrogen ions (p. 414), gives the electrical stimulus (release of positive charges) requisite for muscular contraction. Although the principle is similar to that involved in Galvani's experiments (p. 136), and although fresh light is thus thrown on the problem, the complexity is sufficiently bewildering when we think of the perfect adaptation of the animal machine to the manifold muscular activities involved in even the simplest actions, both voluntary and reflex. To liken the animal to a machine is to pay it a very poor compliment. The only real analogy is to be found in the fact that both are very complex, but inefficient transformers of chemical energy (food or fuel) into kinetic energy. It is true that both wear out in time, but in this respect the animal is vastly superior to the machine, inasmuch as it automatically effects its own repairs. Moreover, it is an essential part of the constitution of the animal, not only that its tissue-cells are always more or less wasting away and being replaced by fresh ones, but that by expending some of its

available energy in the form of nervous or brain activity, it is able to control its own running.

Hormones.—There are other remarkable substances present in both plants and animals which have received much attention during recent years, but whose mode of operation is as yet only very imperfectly understood. When food enters the alimentary canal secretions containing enzymes produced in glands are at once formed, which proceed to operate on the food constituents, rendering them capable of passing into the general blood system, by which they are distributed to all parts of the organism. What is it that induces these glands to secrete ?

The story goes that before the outbreak of the Indian Mutiny certain small cakes called "chapátís" were widely circulated among the Indian towns and villages, and that wherever these were distributed unrest among the natives occurred. In the plant and animal body similar mysterious "messengers" are sent out, from certain centres, which appear to have for their duty the excitation of glandular cells. These bodies are called "hormones," from the Greek word *hormao*, "I rouse to activity." This term was introduced by Professors Starling and Bayliss to indicate the agents that stimulated secretion in the digestive glands. Other hormones, it was discovered, had the power of controlling or even inhibiting the formation of secretions. The first of these to be studied was that called "secretin," which is carried by the blood to the pancreas, where it induces a flow of pancreatic juice into the intestine, carrying the important enzyme, trypsin. The importance of these substances in digestion is now thoroughly recognised, and the administration of extracts containing hormones is well known in medical practice.

The presence of hormones in the sap of plants is also well established, and movements, such as those of the "Sensitive Plant" after contact, are now interpreted as due to the transmission of such "messengers" from leaf to leaf, knocking at each as they pass, like postmen delivering letters at successive housedoors.

Among the hormones are some whose chemical constitution

has been elucidated, and whose synthesis by artificial means has actually been accomplished. One of these, called adrenaline, is a benzene derivative containing a nitrogen atom in its molecule. It is secreted by a small gland adjoining the kidneys (suprarenal gland), and its function is to contract the walls of the bloodvessels of the body and keep them in tone, whilst another hormone, called acetylcholine, has an opposite relaxing effect. Although adrenaline is always functioning normally, it is especially released during the emotion of anger in order to tone up the muscles of the body preparatory to an anticipated fight, and it is this that makes the hairs rise on an animal's back.

Another hormone of known constitution is that secreted by the small glands near the larynx, known as the thyroid glands, and this compound is of enormous importance in the preservation of health of both body and mind. This hormone, called thyroxin, contains iodine, and not only has its constitution been proved by Harington, but he has succeeded recently in synthesising it by purely chemical means.

Vitamins.—Another interesting set of chemical substances that have been identified in the organism are the so-called "vitamins," a name given to them in 1906. They are developed chiefly in plants, but are of great importance to the animal, and are especially valuable in human nutrition. They occur in very minute quantities, but yet they are indispensable. Food is the fuel of the body, for without it the body starves; without the spark to ignite the fuel, coal or petrol is useless; without the vitamins the food cannot be utilised. Careful chemical analysis has taught us the precise nature and relative amounts of the salts in sea-water, and artificial sea-water indistinguishable from the material product can, of course, be manufactured. But while, as everyone knows, marine organisms flourish abundantly in the ocean, they do not do so in artificial sea-water, unless from 1 to 4 per cent. of the latter be added. The supposition is that something like a vitamin is present in the ocean that has not as yet been isolated, or at least has escaped the critical eye of the analyst.

At present we are acquainted with several classes of these

vitamins, which are referred to by letters of the alphabet, for we know little or nothing of their chemical nature, notwithstanding that much research has been carried out upon them by Sir F. G. Hopkins of the University of Cambridge, by Professor Halliburton of King's College, London, and others. The quantity of vitamins necessary to make the difference between a useless and a useful diet is astonishingly small; one drop of unrefined fish-oil was found by Drummond to be sufficient in one case, and yet in that drop the amount of pure vitamin must have been infinitesimal. Life, as Oliver Wendell Holmes said, is "a great bundle of little things." Vitamins are very little things, but we cannot do without them.

Vitamin-A, which is fat-soluble, is found in green vegetables and is stored particularly in the liver of animals; hence it is present in cod-liver oil. It is not destroyed easily by the heat involved in cooking vegetables, but is destroyed by exposure to oxygen (air). This is the principal vitamin which fortifies the animal against disease infection.

Vitamin-B, which is water-soluble, is also found in vegetables, but particularly in seeds, nuts and yeast. It is also found in wholemeal bread, being resistant to the heat of cooking. Recently it has been found that there are two forms of this vitamin: B1, rich in wholemeal bread, and responsible for maintaining a healthy nervous condition in animals, and B2, poor in wholemeal bread, but rich in vegetables, meat and milk and responsible for general health and growth. The animal body has little power of storing these two vitamins (*i.e.*, unlike Vitamin-A), and therefore for health they must be present in the food consumed daily.

Vitamin-C is found more particularly in acid fruits and acts as an anti-scorbutic. But it is very sensitive to oxidation (air exposure), and disappears when food, containing it, is kept or dried. As it is not well stored in the body, regular consumption is necessary for health.

Vitamin-D is usually associated with Vitamin-A in fats and cod-liver oil, and it has recently been proved that it is formed by the action of sunshine on a normal component of animal fats, called ergosterol. It is therefore found in milk, cream and

butter, provided the cow has been exposed to sunshine, and so the amount in these foodstuffs may diminish in winter. This vitamin is necessary for health, being in some way associated with calcium and phosphorus metabolism, and deficiency causes rickets in children as well as dental decay.

Vitamin-E, found in vegetables and stored in the animal, is the sex vitamin. Deficiency causes sex degeneration in animals and sterility.

We have indicated only a very few of the advances in the science of biology that have been made during the past fifty years or so, but perhaps enough has been said to justify the claim that while the other departments of knowledge have forged ahead, the science of life has not lagged behind.

The Riddle of Life.

In spite of the vast amount of knowledge which has been accumulated during the last 130 years, the problem of life still baffles Science, and a whole series of riddles still await solution. How did life first originate on the earth? Does life exist elsewhere? Wherein does life differ from chemical phenomena? Above all, what is the nature of mind and consciousness? These and similar questions present themselves insistently for an answer to the enquiring intellect, but they prove to be as insoluble as the equally insistent questions concerning creation or origin of matter and energy, or the beginnings and end of time.

Regarding the first question asked above, we can, of course, speculate and surmise, as suggested on p. 364, that life took its origin on earth by the operation of purely chemical processes when the ocean was still warm, but it is a lame conclusion at best. If such increasingly complex chemical reactions leading to enzymes and eventually to living organisms did arise (which is thinkable) there is nothing to prove it. "Spontaneous generation" of life has been repeatedly sought for by biologists, working under the conditions of today; and although claims have been made by Bastian and others that life can appear in suitable materials which were previously sterile, all these

claims have broken down on close scrutiny. In short, so far as we know, no life can appear in any non-living material, if proper precautions are observed to exclude spores and cells of existing forms of life, such as bacteria. Living organisms reproduce themselves, and given a long enough period of time, they may change by evolution into other forms of life, but life does not appear of itself, so far as we know, however suitable the conditions may be.

Matter may be induced to undergo chemical changes at will and in the utmost variety or complexity, given the right conditions, but it has never been induced to undergo those complicated biochemical changes, the sum total of which is life, even in its simplest or lowest form. Colloidal matter may be induced to undergo complex changes which simulate the processes and even the movements of life, but the great gulf which divides the non-living from the living has not been bridged yet. Or, to take another illustration, when a cell or living organism dies, with all its complex attributes still apparently complete and unchanged, nothing within the power of Science can once more breathe life into it. It is true that life manifests itself in a great variety of physico-chemical processes, or, as we say, biochemical changes, which like most chemical reactions are sometimes reversible, but the thread of life once broken cannot be repaired: the step is irrevocable and the process irreversible, as all of us know.

Perhaps the nearest analogy in the physical world to this irreversible process is the second law of thermo-dynamics (see p. 132), which implies that energy is always running down from the level of high potential to that of low, and so wasting away as heat which is lost to space. It is as if the universe in general and the sun in particular were a gigantic clock which was once wound up and has been running down ever since; and in this irreversible process of running down life steps in, utilising an inconceivably minute fraction of the total energy, by directing the descent into its own biological channel. However crude the analogy, it is true, nevertheless, that the most outstanding general feature of life as a whole is its wonderful power of utilising solar energy to sustain itself. We call this energy

(indirectly derived from the chemically stored energy of sunshine) food, and it is the oxidation of food which supplies living organisms with their "vital energy," whatever this may be.

There are some who think that vital energy is a thing *sui generis*, essentially different from physical or chemical forms of energy. Others hold that this view is tantamount to admission of our ignorance, and that, when more knowledge is acquired, vital energy will be shown to be merely a complex manifestation of these physical and chemical forms; just as in the old days (prior to Wöhler's synthesis of urea in 1828) it was believed that biochemical organic compounds could not be produced except by the intervention of "vital force." Of course, we know now that these compounds in great complexity and variety can be formed synthetically in the laboratory; but between these compounds and their living function in protoplasm is nevertheless the gap which has not been bridged. And so we must leave it at that.

Science may explain How but not Why; it cannot solve the riddle, though it can rule out many hypothetical attempts. There are other methods of approach to such problems by which truths can be reached, which are satisfying to the human mind, and among these must be reckoned Poetry, Philosophy, and Religion, realms of thought outside the scope of Science, which confines itself to the unemotional and critical scrutiny of Nature; and Science is not qualified to dispute the conclusions arrived at by these methods provided that these conclusions do not conflict with established truth. The iconoclastic and materialistic tendencies of Science in the nineteenth century have, with the greater knowledge of the twentieth, given place to a more tolerant frame of mind in contemplating the inscrutable mysteries of the universe. In all humility the man of Science gazes into the great Unknown; he is now content to say with Shakespeare's soothsayer, "In Nature's infinite book of secrecy a little can I read" and to confute error; but he has (or at least, the majority of this esoteric cult have) learnt that dogmatism can have no place in the Temple of Truth.

If we survey the conditions under which life can exist, we find that they are extraordinarily restricted. Considering the

vast range of temperatures presented by objects in the universe, it is not a little remarkable to find that life is confined to the narrow range of about 30° C., and that this restricted range must have persisted on earth during the many millions of years requisite, for evolution to be possible. If we consider the other planets of the solar system we may conclude that they are certainly not fit abodes for life as we know it here. Mercury is too hot on one side and too cold on the other, though life may be possible along the dividing band between them. Venus is too hot also, but it is possible that there may be the initial stages of life here, and that when the planet has receded from the sun sufficiently to have a climate like ours, life may be in full development at a time when it will be extinct on earth. Mars, of all the planets, is the one most likely to sustain life similar to that on earth, though, of course, its climate is cold with rather extreme variation of temperature; the supposedly artificial canals, as we have seen, have no real existence, but the seasonal changes in colour of the surface and the presence of moisture and oxygen in the Martian atmosphere are suggestive at least of vegetation, whose growth and appearance would depend on the scant watering of desert regions.

The other planets are quite ruled out as abodes of life such as we know it, though incipient forms of life would be thinkable (as on Venus) wherever the temperature may suit. As for stars and nebulæ, these are ruled out on account of their high temperatures. Relatively few stars, if any, can have given birth to planets similar to our solar system, as the chances are very remote against encounters such as our sun experienced (p. 335). And if there are other planets (say, in our own galactic system) which, of course, could not be detected telescopically, the chances are small that they would be suitable as abodes for life in the stage of development found on earth, because of the limited range of temperature requisite spread over such a long period of time. Such time, of course, is very short as astronomical times go, but it is the coincidence of time and narrow temperature range that seems to make the chances so slender. We cannot by any means say that the earth is unique, though it almost looks as if it were, but we can say that

the conditions on earth are most extraordinarily well adapted to the existence and evolution of life.

If we cast our minds back to the early days of evolution before distinct animal and vegetable forms had bifurcated from the tree of life, we may suppose that some of the earliest unicellular organisms, only remotely similar to the present bacteria (see p. 419), had begun to develop a green colour by the acquisition of chlorophyll and were henceforward dependent on solar energy. These aquatic organisms must have later tried all sorts of experiments (so to speak) in adapting themselves to changing surroundings; and over a period of many millions of years all sorts of varieties or species would appear, now dependent on the oxygen generated by their chlorophyll (this gas was now increasing everywhere) and apparently on nitrates or nitrites for their protoplasm. As they lived and died their dead bodies were used as a source of energy for the life of lower organisms, like the bacteria, which produced from them the necessary nitrites and nitrates.

Balance of Life.—So a balance or cycle commenced which persists to the present day, a balance by which dead organisms or cells are converted through the activity of bacteria into useful nitrates or nitrites necessary for vegetative life. After a while some of these early unicellular organisms must have discovered a short cut by which, instead of manufacturing their own food through the agency of chlorophyll, they ingested the bodies (dead or alive) of other organisms, in a similar way to the bacteria. How this began we cannot say, but probably at first it was mainly a matter of size; those cells which discovered the trick of growing to a larger size could attack, ingest, and absorb smaller cells in the same kind of way that an amœba cell does today with bacteria (see p. 421).

At any rate, in some such way the bifurcation began which ultimately led to the animal kingdom, in which (except the most primitive) the individuals possess no chlorophyll, and so have no power of manufacturing their own food reserves. Although, therefore, animals in the last analysis can be regarded as parasitic on the vegetable world (because even carnivorous animals depend ultimately for food on animals which are

herbivorous), it is nevertheless true that the appearance of animals, with their special functions, greatly helped to establish the chemical balance of life, by which the same substances (carbon dioxide, ammonia, nitrates, etc.) are endlessly utilised in a continual cycle of biochemical changes for the maintenance of life. Take, for example, the balance of life as it exists today. The raw material is in the water or soil and air, in the form of moisture, oxygen, carbon dioxide, ammonia, nitrites and nitrates, phosphates, etc., all wanted by the plant. The simplest case, perhaps, is aquatic, say a small pond, where the first step in the cycle is the multiplication (from spores and cells originally there) of a whole host of green unicellular algæ (grouped under the general title " phytoplankton ") all actively growing and increasing by cell-division, under the influence of solar energy, by utilising the chlorophyll function. So by photosynthesis (p. 440) they liberate oxygen by decomposing carbon dioxide dissolved in the water; the dissolved nitrite and nitrate, phosphate, etc., also disappearing from the water and going to make up the protoplasm which is so constantly being manufactured. It may be noted here that water, as it appears in Nature, is never pure, but always contains more or less dissolved salts and CO_2. In ordinary " hard " water, the CO_2 is partly present, free, as carbonic acid (H_2CO_3), but it is mostly in combined form as calcium bicarbonate, $Ca(HCO_3)_2$, and magnesium bicarbonate. But as these are unstable, and readily pass into carbonates (*e.g.*, $CaCO_3$) and free CO_2 (as, for instance, when hard water is " softened " by boiling), these bicarbonates serve as reservoirs for CO_2 in photosynthesis.

If nothing else happened the process of multiplication (*i.e.*, increase in numbers of cells) would come to an end when one or other of the essential substances dissolved in the water became exhausted. But long before this happens minute animal forms of life (originally present say in a resting condition), such as rotifers, amœbæ, and other protozoa grouped under the general title " zooplankton," commence feeding on the phytoplankton, and so thrive and multiply. These in their turn fall a prey to larger forms of animal life, such as small crustaceans, which in their turn may be devoured by still larger

organisms, such as fish, larvæ of insects, etc. All the animal forms produce excrement, some die, and some of the algal cells die or any other vegetation may die, and as we say decay.

Let us see what happens. All this excremental, dead or decaying matter is food for numberless destructive and putrefactive bacteria or fungi, which, utilising the chemical energy so available, multiply and thrive; but in so doing they ultimately convert the waste material, by a series of steps, into simple inorganic compounds, carbon dioxide, nitrites, nitrates, phosphates, etc. These bacteria, however, cannot multiply indefinitely, because, apart from the limited food (waste) material, their numbers are continually reduced by the rotifers, amœbæ, etc., which prey upon them. So as a result of the sequence, we have a continual return of the inorganic substances essential for the growth of the microscopic (or other) plant life, which ultimately sustains the larger animal life, such as fish, etc.; the cycle is complete and the complicated balance of life maintained.

So it is also in the sea, where phytoplankton is the primary source of all food for fish, etc., and, therefore, eventually (to some extent) that of man. As might be expected, this primary food source is at a minimum in the dark months of winter; but in spring, with the great increase of sunlight, there is a great outburst of plankton production, which increases till some limiting factor supervenes, such as shortage of one of the essential chemical substances, like carbon dioxide or phosphates.

So it is also on land, where, however, the cycle runs a different course. Here it is the higher plants which form the principal foodstuffs, by which directly or indirectly all animals are sustained, including man. Whether it is grasses, clover, etc., for the grazing of cattle, or cereals, or vegetables, the same kind of cycle is at work as that in the water. Carbon dioxide (of the air—see p. 442) is always available for the photosynthetic activity of chlorophyll, yielding carbohydrates, etc., but other inorganic materials, necessary for the life of the plant (nitrates, phosphates, potassium salts, etc.) and found in the soil, may be more or less exhausted in a single season of growth unless returned. It is the function of bacteria to carry on this

efficient service in the soil by flourishing upon dead nitrogenous organic matter of all kinds, excrementa, etc., which in agriculture are applied in the form of manure. And this useful work of destruction or scavenging, assisted as it is by animal forms of life (protozoa, such as amœbæ, also worms), goes on incessantly while we are scarcely aware of it. Without it the world long ago would have been littered with fallen leaves and rubbish sufficient to swamp everything on it, but in the balance of life all this waste and decaying material disappears because it is broken down by bacterial agency into simpler and soluble inorganic materials, necessary for the life of the growing plant.

It need hardly be said that in this wonderful cycle the ideal balance of life is often faulty, or broken by some agency or other. Agriculture and horticulture strive to maintain an ideal balance for economic reasons, but they fail and are wasteful to the extent that they have not yet discovered a satisfactory solution of the sewage problem, by which its valuable and potential plant-food materials can be returned to the land. Again in "soil sickness" we have a wrong balance; through over-manuring the soil has become so relatively rich in animal organisms (protozoa) that, since their food consists of soil bacteria, the beneficent nitrate-producing bacteria cannot multiply sufficiently to meet the nitrate needs of the plant in its growth.

In Nature, which is notoriously spendthrift, the balance is maintained by haphazard methods, and wherever it fails, such as in desert, rocky, or snowy regions, life of any kind has only a precarious hold. So complex is the balance that the deficiency of one single constituent, such as iron or chlorine (only utilised in very small quantities by plants), or excess of some acidic substance, may produce barrenness, or at least economic failure in agriculture; and it is not always easy to detect what the cause is. On the other hand, when the natural balance is good and requires only small assistance from Man, as is the case with most of the soil of England, all should be well, because here Nature is kind. There may not be the riot of life and colour such as the tropics provide, yet we may feel grateful for

the living charm and diversity of the countryside, so far as its beauty has not been outraged by the vile thoughtlessness of Man.

Humanity.—And yet Man surely is the greatest miracle in all Nature's wonderful category, and it is not mere anthropocentric conceit to say to. Regarded as the latest of the many experiments which Nature has tried in evolving new forms (mostly failures which have disappeared), perhaps physically he has no great claims to distinction beyond an appealing beauty in the best specimens; mentally he is unique, and the "divine afflatus" marks him out from the beast. Without his intellect, and above all the Science and Art which he has made his own peculiar domain, he would be rather a poor creature, as indeed he is at worst; at best he is little short of a god. As Shakespeare in *Hamlet* says (Act II., Scene 2):

> "What a piece of work is a man! How noble in reason! How infinite in faculties! in form and moving how express and admirable! in action, how like an angel! in apprehension, how like a god! the beauty of the world! the paragon of animals! And yet to me, what is this quintessence of dust?"

Man certainly cannot boast of his pedigree; his ancestors of some 400,000 years ago must in appearance have resembled Neanderthal man, whose coarse and brutal gorilla-like features can be easily reconstructed from the fossil remains we have.

According to one of the highest authorities on Anthropology, Professor Elliot Smith, the human line of descent must have branched off from that of the ape in early Miocene times about two million years ago, and during this period various offshoots or attempts at Man have become extinct. Some early remains, those of the recently discovered Taungs skull in South Africa, represent an ape with distinctly human affinities, much more human than any existing ape, while the later Java remains (Pithecanthropus) are half human, so as to be entitled to the name of Ape-Man; but they were an offshoot and not on the main line of descent. The next important human remains are those discovered at Piltdown in Sussex; they date back about 500,000 years and certainly represent primitive man (Eoanthropus), who has not yet lost his ape-like character altogether, but even he is an extinct offshoot, as also are the later

Heidelberg man, the still more recent Neanderthal man, and the most recent of all (Rhodesian man of Broken Hill). All these "missing links" are abortive attempts at Man in the making, and all have led to blind alleys, as have no doubt other forms yet to be discovered, and the main line of descent has not yet been discovered.

Whilst, therefore, we cannot trace by fossil remains the direct line of modern man's ancestry, during the last few hundred thousand years, there is no difficulty in reconstructing approximately the genealogical tree of humanity in general, including the extinct races. We can say with tolerable confidence that the first critical divergence from the Ape-stock, which was destined to give birth to humanity, began in the far-off ages somewhere towards the close of the Oligocene period (p. 430); and there is every reason to believe that this divergence began somewhere in South Central Asia. What was the stimulus to this great event we cannot say, but it is important to remember, as Professor Barrell first pointed out, that at this time the Himalayan range of mountains did not exist, and if the gradual rise of this colossal range about the beginning of the Miocene period trapped some of the apes to the north, cutting them off from their warm forests, the survivors in the relatively cold treeless plains to the north would be compelled to abandon their arboreal mode of life. They would have had a hard fight to exist, and only survived by acquiring carnivorous habits. An ever enlarging brain, as the struggle for existence sharpened their wits, by eliminating the weaker members, and the increased use of their hands, gave this race of beings new powers, which during the Miocene and Pliocene periods were more and more differentiating them from their ape-like relatives in the forests. At the beginning of the Pleistocene period, say half a million years ago, they were migrating and spreading to Europe and Africa, as incipient and distinct races, already referred to, now extinct.

Somewhere about 300,000 years ago one of these races, a cousin-branch of the primitive Neanderthal man, gave birth to our own species (*Homo sapiens*). We cannot in the least say how this happened, or what it was in the surrounding

conditions which eliminated the cousin races and favoured the selection by Nature of this new line of beings, a race which was destined to give rise by branching to the various races of Man existing today. But it is highly probable that it was superior brain-power and skill in meeting difficulties, or in fashioning primitive tools, which gave this race the advantage and enabled it to continue while the others perished. At all events, somewhere in the line of descent within the last 300,000 years or so offshoots, consisting of rather less efficient modern races, branched off, first the Australian, then the negro, and finally the Mongolian races, each of which has held its own till today; whilst the main branch of Nordic man, with its recent offshoots, the Alpine and Mediterranean races respectively, appears as the dominant intellectual race of today. And all these modern races have gone through more or less similar phases in development as indicated by the tools they have used in the past. The white races leading the van have passed successively through several stone ages of implements, and a bronze age, prior to their rise to civilisation (p. 484). Earlier stone ages (palæolithic) seem to have intercalated with the last two ice-ages, over 50,000 years ago, and the later (neolithic) age is post-glacial, lying within the last 10,000 years, whilst the recent bronze age brings us to the verge of history, which, of course, only goes back a few thousand years. History and civilisation are but things of yesterday, and even if we consider the long span of 300,000 years since *Homo sapiens* first appeared on earth, during which he has advanced ever to higher and higher levels of achievement, how short it seems in comparison with the 6 million million years during which the sun has been shining, or even the relatively recent time of 2 to 3 thousand million years ago, when the earth was born out of the sun! Measured by a scale of magnitudes such as these, humanity is like a babe in swaddling clothes, feeding at the breast of its mother earth; indeed if we make a comparison of their respective ages, on a different scale from that we adopted in the case of the planets (p. 335), so as to get a suitable simile, we may say that if the mother is thirty years old the babe of humanity is little more than a day. Will it ever live to grow up and

understand the realities of the great world around it, which at present it perceives only in a dazed infantile kind of way? We shall never know.

§ vi. Envoi

Physicists picture to us, either a space-time continuum or a universal ether filling all space, and the appearance in it of electrons and protons that combine to form atoms. The Chemists tell us how these atoms unite into molecules, and how molecules in turn group themselves into familiar matter. Astronomers teach us how suns are formed, stupendous in size and in a state of intense activity. Our sun radiates energy, which agitates molecules in plants, causing them to form more and more complex molecules that in some mysterious way link themselves into protoplasm. In this aggregate of molecules appear entirely novel characters, for, unlike the simpler compounds we call inorganic, protoplasm has the power of self-moving, self-feeding and self-multiplying, provided it be kept stimulated by ether waves from the earth's prime source of energy, the sun, and supplied with oxygen and other materials. It has become a primordial living cell.

But the evolutionary process does not stop there. The cells may link up in an infinite number of ways, ever increasing in complexity, till at last we reach the aggregates of cells we know as plants and animals. And contemplating the continuity, from generation to generation, since the dim ages of the past till today, we see that, though individuals and races have gone, the germ plasm which has yielded the tree of life has never died—in it we perceive the nearest approach to immortality known to Science. In the highest branches we begin to recognise the birth of purpose, foresight, will—the genesis of mind—till in man himself we reach the climax, and contemplate an organism able to look back over the long, long story of his own origin from the primordial protons and electrons dotted through ethereal space. The story is indeed a marvellous one, if only we take the pains to read it, and the most wonderful fact in it is, that it should culminate in a being able to comprehend it all.

But does it end with him? Some say "Yes," and would have us believe that when this thinking machine is destroyed or wears out, the units of which it is composed follow down the pathway they have climbed with so much toil and resolve themselves into the primeval cells, molecules and atoms from which they arose. There are some who would have us believe otherwise. They are loath to think that a being evolved with so much labour through countless eons of time should perish and leave nothing behind it but a memory. Both views have had and still have ardent supporters. Which is nearer the truth is a question that has puzzled the sages of the past, as it will doubtless puzzle generations of wise men yet unborn. We are ourselves both judge and jury; alas! we are also the prisoners at the bar.

EVOLUTION: AT THE MIND'S CINEMA

1.

I turn the handle and the story starts;
  Reel after reel is all astronomy,
Till life, enkindled in a niche of sky,
  Leaps on the stage to play a million parts.

2.

Life leaves the slime and thro' all ocean darts;
  She conquers earth, and raises wings to fly;
Then spirit blooms, and learns how not to die—
  Nesting beyond the grave in others' hearts.

3.

I turn the handle; other men like me
  Have made the film; and now I sit and look
In quiet, privileged like divinity
  To read the roaring world as in a book.

  If this thy past, where shall thy future climb,
  O Spirit, built of Elements and Time?

J. S. HUXLEY

USEFUL DATA

10^n = 1 followed by n noughts; $10^{-n} = \frac{1}{\text{1 followed by } n \text{ noughts}}$.

Example: 5 million=5×10^6; 5 millionths=5×10^{-6}.

Metre=39·37 inches.

Centimetre (cm.)=10^{-2} metre (·3937 inch).

Millimetre (mm.)=10^{-3} metre.

Micron (μ)=10^{-4} cm.

$\mu\mu$=10^{-7} cm.

Ångström unit (Å.U.)=10^{-8} cm.

Cubic centimetre (c.c.)=10^{-3} litre (·061 cu. inch).

Gram=mass of 1 c.c. water at 4° C. (about $\frac{1}{28}$ ounce).

Velocity of light=186,000 miles (about 3×10^{10} cm.) per second.

Light-year=$5{\cdot}9 \times 10^{12}$ miles.

Par-sec=3·25 light-years.

Electron, mass=$8{\cdot}9 \times 10^{-28}$ gram.

,, diam.=about 3×10^{-13} cm. probably.

Ampère=$6{\cdot}3 \times 10^{18}$ electrons per second.

Proton (hydrogen nucleus), mass=$1{\cdot}66 \times 10^{-24}$ gram.

,, ,, ,, diam.=2×10^{-16} cm.

Hydrogen atom, diam.=about $1{\cdot}1 \times 10^{-8}$ cm.

Molecules, diam.=about 2 to 6×10^{-8} cm.

,, number per c.c. of any gas = $2{\cdot}7 \times 10^{19}$ (at 0° C. and 760 mm.)

Avogadro's constant (number of molecules in 22·4 litres of any gas) =$6{\cdot}06 \times 10^{23}$ (at 0° C. and 760 mm.).

Velocity of hydrogen molecules (mean)=$1{\cdot}69 \times 10^5$ cm. (at 0° C. and 760 mm.).

Mean free path of hydrogen molecules=$1{\cdot}6 \times 10^{-5}$ cm. (at 0° C. and 760 mm.).

Wave-length (λ) of visible spectrum=about 4,000 to $8{,}000 \times 10^{-8}$ cm.

,, of infra-red (solar)=about ·8 to 12·8 μ.

,, of ultra-violet (solar)=about 2,500 to $4{,}000 \times 10^{-8}$ cm.

Wave number = $\frac{1}{\lambda}$.

CHRONOLOGICAL TABLE

Only the leading discoveries are listed—viz., those which are milestones in the progress of general Science. Abbreviations: fl.=flourished; ca.=about.

B.C.		
ca. 600.	THALES.	Solstices and equinoxes; observes electrification of rubbed amber (elektron).
ca. 600.	ANAXIMANDER.	Moon's phases; geography.
fl. 536.	PYTHAGORAS.	Heliocentric cosmogony; geology; philosophy.
fl. 500.	HERACLEITUS.	Theory of fire as first principle.
ca. 440.	EMPEDOCLES.	Four elements (fire, earth, air, and water).
fl. 430.	SOCRATES.	Philosophy. Study of mankind.
fl. 420.	DEMOCRITUS.	Atomic theory of ancients.
fl. 420.	HIPPOCRATES.	Biology; rational medicine (human and veterinary).
fl. 390.	PLATO.	Philosophy.
fl. 340.	DIOPHANTUS.	Mathematics (invention of algebra).
fl. 340.	ARISTOTLE.	Anatomy; botany; physics; philosophy.
ca. 306.	EPICURUS.	Speculative philosophy; nature of atoms and vacuum.
fl. 300.	THEOPHRASTUS.	Botany; chemistry; electricity.
fl. 300.	EUCLID.	Geometry.
fl. 298.	PTOLEMY SOTER.	Founds Alexandrian Library.
ca. 294.	ZENO.	Founds Stoic philosophy.
ca. 250.	ARCHIMEDES.	Mathematics; mechanics.
fl. 250.	ARISTARCHUS.	Heliocentric astronomy; discovers precession of equinoxes.
ca. 240.	ERATOSTHENES.	Astronomy; ecliptic; measures earth's circumference.
fl. 160.	HIPPARCHUS.	Star catalogue; position of equinoxes; founded geocentric theory of universe.
ca. 116.	VARRO.	Veterinary medicine.
ca. 60.	LUCRETIUS.	Atoms and matter; author of "De Rerum Naturæ."
ca. 25.	STRABO.	Geography and geology.
A.D.		
fl. 60.	PLINY (THE ELDER).	Chemistry; metallurgy; description of acids, soap, glass, etc.
fl. ca. 70.	DIOSCORIDES.	Botany and "De Materia Medica"; distillation; metallurgy.
fl. 140.	PTOLEMY (CLAUDIUS PTOLEMÆUS)	Propounder of erroneous geocentric theory of astronomy.

A.D.		
fl. 170.	GALEN.	Anatomist; physiologist; authority on pharmacy, hygiene and disease.
ca. 250.		Rise of Neo-Platonism and increasing mysticism in Science.
ca. 280.		General decay of Science, but chemical industries active (dyeing and metallurgy, glass).
285.		First division of Roman Empire (by Diocletian) into East (Byzantium) and West (Rome).
ca. 290.		Diocletian orders destruction of Egyptian books on alchemy and magic.
300-400.		Roman Empire threatened by Goths and Vandals. Rise of alchemy in the Alexandrian schools of learning.
325.		Christianity recognised by Roman Empire (Constantine).
ca. 380.	HYPATIA.	Leading exponent of mystical Neo-Platonism; lectures on mathematics and astronomy (in Alexandria).
385.		Destruction of Alexandrian Library (in the Serapeion) of 500,000 books.
400-500.		Entire Roman Empire attacked by Huns, Goths and Vandals. Mysticism and magic introduced into alchemy.
fl. 400.	SYNESIUS.	(Alexandrian savant) describes metallurgy with idea of transmutation; increasing mysticism.
410.		Sack of Rome by Alaric.
ca. 412.	ZOSIMOS.	(Bishop of Rome) authority on alchemy.
429.		Vandals invade Roman Empire in Africa (Genseric).
440.		Romans finally desert Britain.
455.		Sack of Rome by Vandals (Genseric) followed by twenty years' tumult and anarchy.
476.		Extinction of Roman Empire of the West (Odoacer).
500-600.		Byzantium (centre of eastern Roman Empire) and Alexandria, chief seats of civilisation.
ca. 500.		Zenith of alchemy at Alexandria.
fl. 520.	OLYMPIODOR.	(Alexandrian savant) associates metals with planets in his "Meteorologica."
ca. 600.		Alchemy gets a foothold in Byzantium (now Constantinople).

A.D.		
600-700.		Rise of Arabian civilisation; philosopher's stone and elixir of life chief goals in alchemy.
641.		Final destruction of Alexandrian Library, by Saracens; capture of Alexandria by Omar, and irruption of Arabs; end of Alexandrian culture.
ca. 680.	KHALID BEN YEZID.	Describes alchemical apparatus and mystic signs of alchemy.
700-800.		Rise of Arabian alchemy and Eastern civilisation.
717.	CALLINICUS.	Uses "Greek fire" in defence of Byzantium.
800.		Harun-al-rashid orders translation of Ptolemy's "Almagest" (astronomy).
825.	BEN MUSA (IBN MÛSÂ AL-KHOWARÎZMÎ).	Introduces algebra into Europe. Wrote first Arabian book on algebra (Al-jebr).
fl. 890.	GEBER (JĀBIR IBN HAIYĀN).	Rediscovers chemical facts; skilled experimentalist. Describes separation by distillation, sublimation, etc., and writes oldest chemical book, "Summa Perfectionis."
ca. 900.	ALHAZEN (earlier).	Works on Arabian pharmacy leading to botany and chemistry.
ca. 910.	RHAZES.	Physician and alchemist.
ca. 930.	ALBATEN. ALBATINI.	Observations on earth's orbit and obliquity of ecliptic.
ca. 940.	AL SŪFI.	Revises Ptolemy's star catalogue.
977.	IBN JUNIS.	Accurately records solar eclipse, also one in 978.
1000.		Abassid rule in the East; schools of science and medicine at Bagdad, Alexandria, Cordova, etc.
fl. 1010.	ALHAZEN (later).	Rediscovers Ptolemy's optics and use of lens; observes atmospheric refraction.
ca. 1020.	AVICENNA (IBN SINA).	Writes handbook of medicine; pharmaceutical applications of alchemy, and attempted transmutation of lead into gold.
ca. 1170.	AVERRHOES.	Treatises on astronomy and medicine; revival of Aristotelian theories and philosophy.
fl. 1240.	ALBERTUS MAGNUS.	Revives experimental method in science; exponent of Aristotle; books on alchemy, metallurgy and minerals.
ca. 1250.	ROGER BACON.	(1214-1294) Insists on experimental method in Science; explains tides, rainbow, perspective, etc. Gunpowder mentioned. Greatly ahead of his time.

A.D.		
ca. 1280.	Raymond Lully.	(1235-1315) Development of alchemical experimental technique.
1420.	Ulugh Beg.	(Grandson of Tamerlane the Great) founds astronomical observatory at Samarkand.
1425.	Johannes Gutenberg.	Invention of printing.
ca. 1430.	Basil Valentine.	(1394-1450) Extends empirical chemistry; publishes "The Triumphal Car of Antimony."
1450.	Valerius Cordus.	Observes nodules on lupin roots (due to nitrogen-fixing bacteria).
fl. 1490.	Leonardo da Vinci.	(1452-1519) Painter, scientist and engineer; astounding genius far ahead of his time, anticipating modern discoveries.
1492.	Columbus.	Discovers America.
1507.	Copernicus.	(1473-1543) Disproof of Ptolemaic (geocentric) system of astronomy. Founder of modern (heliocentric) system.
1519.	Magellan.	Circumnavigates the globe.
fl. 1530.	Paracelsus.	(1493-1541) Decline of alchemy and rise of Iatrochemistry (in service of medicine).
ca. 1550.	Gesner.	Classification of plants and animals.
fl. 1580.	Tycho Brahé.	(1546-1601) Rise of astronomy; Rudolphine tables.
1590.	Jansen.	Invention of microscope.
1600.	Bruno.	Burnt at stake for defending Copernican (heliocentric) system.
ca. 1600.	Gilbert.	Discovers frictional electricity and the earth's magnetism.
ca. 1600.	Brunfels, Cordus, etc.	Herbalists.
ca. 1600.	Drebble.	Invention of thermometer, also invented by Galileo (1597).
ca. 1605.	Galileo.	(1564-1642) Invention of telescope (see Lippershey); discovery of Jupiter's satellites (1610), phases of Venus, etc.; pendulum, acceleration and laws of motion (1602).
1608.	Lippershey.	Invents telescope (see Galileo).
ca. 1612.	Kepler.	(1571-1630) Laws of planetary motion.
1614.	Napier.	Discoverer of logarithmic system in mathematics.
ca. 1615.	Francis Bacon (Lord).	(1561-1626) Establishes inductive method of reasoning from observed facts of science; "Novum Organum," 1620.
1619.	Harvey.	(1578-1657) Discovers circulation of the blood.

A.D.		
ca. 1620.	J. B. VAN HELMONT.	Last claim for actual transmutation of metals in alchemy (mercury into gold).
1631.	GASSENDI.	Transit of Mercury first observed.
1633.	TORRICELLI.	(1608-1647) Inventor of barometer; discovers pressure of earth's atmosphere; vacuum.
1639.	HORROCKS (HORROX).	Transit of Venus first observed.
ca. 1640.	DESCARTES.	(1596-1650) Cartesian system of philosophy and system of co-ordinates as framework of geometrical space.
1650.	GUERICKE.	Invents air-pump (vacuum); investigates static electricity.
1650.	PASCAL.	Investigates atmospheric pressure.
1660.		Royal Society founded in London.
ca. 1660.	ROBERT BOYLE.	(1627-1691) "Father of chemistry"; publishes "The Sceptical Chymist" (1661); discovers law of pressure with gases (1660).
ca. 1660.	F. M. VAN HELMONT.	Discovers conservation of matter; discovers carbon dioxide, and extends chemical knowledge.
1663.	NEWTON.	(1642-1727) Founder of new system of space and time; discovery of binomial theorem and calculus in mathematics.
1665.	ROBERT HOOKE.	Discovery of biological cell structure. Publishes "Micrographia" and anticipates the undulatory theory of light.
1666.		Paris Academy founded.
ca. 1667.	JOHN RAY.	Classification of plants and animals.
ca. 1669.	STENO.	Shows importance of denudation in geology.
ca. 1670.	MALPIGHI.	(1628-1694) Discovers blood corpuscles and capillaries.
ca. 1670.	MAYOW.	(1645-1679) Investigates nature of air and combustion.
1676.	ROEMER.	Determines velocity of light.
ca. 1670.	MAYOW.	Discovers "spiritus nitro-æreus" (oxygen) in air.
1674.	MAYOW.	Discovers nitrogen, later called "mephitic air."
ca. 1675.	NEWTON.	Discovery of nature of light (spectrum analysis); corpuscular theory of light and postulation of "luminiferous ether"; invents reflecting telescope.
ca. 1680.	BARTOLINUS.	Discovers double refraction.
ca. 1680.	NEHEMIAH GREW.	Discovers chlorophyll of plants.
ca. 1683.	LEEUWENHOEK.	Discovery of bacteria and animalculæ (microbes).
ca. 1684.	NEWTON.	Law of gravitation; cause of tides and precession of equinoxes.

A.D.		
fl. 1686.	LEIBNITZ.	Mathematician and philosopher.
1687.	NEWTON.	Immortal work "The Principia" published.
1690.	HUYGENS.	(1629-1695) Discovers double refraction and propounds the undulatory theory of light.
ca. 1690.	SAUVEUR.	Discovers sound waves.
1697.	STAHL. BECHER.	(1660-1734) Found the erroneous theory of Phlogiston.
1703.	BOETTGER.	Discovers porcelain.
ca. 1710.	STEPHEN HALES.	Discovery of sap pressure in plants.
1721.	FAHRENHEIT.	(*b.* 1686) Invents thermometer scale.
1726.	BRADLEY.	(1692-1762) Discovers aberration of light; astronomical parallax and nutation.
1729.	STEPHEN GRAY.	Discovers conduction of electricity.
1740.	CELSIUS.	(*b.* 1701) Invents centigrade thermometer scale.
1745.	MUSSCHENBROEK.	Invents Leyden jar.
1745.	WATSON.	Leyden jar of Musschenbroek improved by Watson.
1747.	LIND.	Empiric observations on scurvy-prevention (vitamins thus foreshadowed).
ca. 1749.	BUFFON.	Puts forward universal ocean theory to explain origin of fossils.
1749.	BENJAMIN FRANKLIN.	Identifies lightning with electricity.
ca. 1750.	GUETTARD.	Discovers origin of fossils in rocks.
1752.	BENJAMIN FRANKLIN.	(*b.* 1706) Invents lightning conductor.
1755.	JOSEPH BLACK.	(1728-1799) Researches on fixed air (CO_2) and alkalies; introduces balance into chemistry.
1755.	LINNÆUS.	(*b.* 1707) Publishes "Systema Naturæ" and invents binomial nomenclature.
1762.	JOSEPH BLACK.	Discovers latent heat.
1762.	PLENCIZ.	Anticipates microbe theory of disease.
ca. 1765.	DESMAREST.	(*b.* 1725) Investigates denudation and volcanic rocks.
1769.	JAMES WATT.	(1736-1819) Invents steam engine.
1774.	MASKELEYNE.	Determines density of earth (Schehallion experiment).
1774.	JOSEPH PRIESTLEY.	(1773-1804) Discovers oxygen; shows oxygen is liberated by plants.
1774.	SCHEELE.	(1742-1786) Discovers oxygen and chlorine.
1775.	LAVOISIER.	(1743-1794) Founds modern chemistry by true theory of combustion, and proof of the nature of oxygen.

A.D.		
1777.	SCHEELE.	Discovers effect of light on "horn silver" (AgCl), foreshadowing photography.
1779.	INGENHOUSZ.	(1730-1799) Discovers plant respiration.
1780.	GALVANI.	(1737-1798) Discovers effect of electricity on animals.
1781.	SIR W. HERSCHEL.	(1738-1822) Discovers Uranus and explores the heavens, nebulæ, etc.; discovers infra-red rays.
1784.	HENRY CAVENDISH.	(1731-1810) Proves composition of water, and detects "impurity" (argon, etc.) in air.
ca. 1785.	LAVOISIER.	Overthrow of phlogistic doctrine, after Cavendish's experiments.
fl. 1786.	CHLADNI.	Investigates sound vibrations.
1787.	J. A. C. CHARLES.	Examines influence of temperature on volume of gases (*see* Gay Lussac's law).
1789.	LAVOISIER.	"Elementary Treatise on Chemistry."
1789.	DE JUSSIEU.	Classification of plants.
1789.	KLAPROTH.	(1743-1817) Discovers uranium.
1789.	DE SAUSSURE.	(1740-1799) Investigates geology of the Alps.
fl. 1790.	BODE.	Law of planetary distances.
ca. 1790.	RITTER.	Discovers ultra-violet rays.
1793.		Learned societies suppressed in French Revolution.
1795.	HUTTON.	(*b.* 1726) Publishes "Theory of Earth."
1796.	INGENHOUSZ.	Discovers carbon dioxide assimilation by plants (now called photosynthesis).
1796.	JENNER.	Introduces vaccination.
1796.	LAPLACE.	(1749-1827) "Système du Monde" and nebular hypothesis.
ca. 1797.	BERTHOLLET.	(1748-1822) Formulates "mass action" theory of chemistry.
1798.	MALTHUS.	Publishes "Essay on the Principles of Population."
1798.	COUNT RUMFORD.	(1753-1814) Discovers nature of heat; founds Royal Institution.
ca. 1800.	PROUST.	(*b.* 1755) Demonstrates law of definite and multiple proportions in chemistry.
1800.	VOLTA.	(1745-1827) Discovers current electricity and invents electric battery.
1801.	PIAZZI.	Discovers Ceres, the first of the asteroids.
1802.	GAY-LUSSAC.	(1778-1850) Law of expansion of gases (see Charles).
1802.	WEDGWOOD.	Using silver nitrate, founds the art of photography (also Davy).

A.D.		
1802.	WOLLASTON.	Discovers dark lines in solar spectrum (Fraunhofer lines).
1803.	HENRY. JOHN DALTON.	Law of partial pressure (solution of gases).
1804.	DE SAUSSURE.	Discovers carbon dioxide function in plant physiology and nature of assimilation.
1805.	JOHN DALTON.	Publishes first table of atomic weights.
1806.	HUMPHRY DAVY.	Discovers electrolysis.
1808.	JOHN DALTON.	(1766-1844) Founds atomic theory.
1808.	HUMPHRY DAVY.	(1778-1829) Discovers sodium and potassium by electrolysis; shows chlorine to be an element.
1808.	GAY-LUSSAC.	Law of volumes (gaseous combination).
1808.	MALUS.	(1775-1812) Discovers polarisation of light.
ca. 1810.	YOUNG.	(1773-1829) Discovers interference of light waves, and examines polarised light.
1811.	AVOGADRO.	(1776-1856) Equal volumes of gases shown to contain same number of molecules.
ca. 1811.	FRESNEL.	Investigates the nature of polarised light.
ca. 1811.	W. SMITH.	(*b.* 1769) Investigates geological strata of England.
1813.	DE CANDOLLE.	(*b.* 1778) Publishes first textbook of Botany.
ca. 1813.	SAINTE-HILAIRE.	Theory of adaptation in animals.
1814.	DAGUERRE.	Invents photography.
1814.	FRAUNHOFER.	Investigates dark lines of solar spectrum.
1815.	HUMPHRY DAVY.	Invents safety lamp.
1815.	LAMARCK.	(1744-1829) First idea of evolution, by theory of biological use and disuse.
1815.	PROUT.	Hypothesis that all elements were built up out of the same ultimate stuff (protyle).
1817.	CUVIER.	(1769-1832) Animal classification.
1817.	DÖBEREINER.	Discovers families among elements.
1819.	BERZELIUS.	(1779 - 1848) Electro - chemical theory formulated.
1819.	PELETIER; CAVENTOU.	Investigate chlorophyll.
1819.	DULONG AND PETIT.	Law of atomic heat.
1820.	EDMUND DAVY.	Observes catalysis (platinum).
1820.	MITSCHERLICH.	Law of isomorphism.
ca. 1820.	SIR J. HERSCHEL.	(1792-1871) Catalogues southern stars; discovers "Magellanic clouds."
1820.	OERSTED.	(*b.* 1777) Discovery of electromagnetism.
1820.	AMPÈRE.	(*b.* 1775) Relates electricity to magnetism.

A.D.		
1824.	CARNOT.	(*b.* 1796) Discovers relation between heat and work (foundation of thermodynamics).
1825.	FARADAY.	(1791-1867) Discovers benzene.
1827.	SIR J. HERSCHEL.	Identifies sodium, etc., in the sun.
1827.	OHM.	(*b.* 1789) Discovers electrical conductivity and electromotive force.
1828.	BERZELIUS.	Discovers thorium.
1828.	WÖHLER.	(1800-1882) Synthesis of urea and overthrow of doctrine of "vital force."
ca. 1830.	LIEBIG, ETC.	Recognition of unorganised ferments (amygdalin, etc.).
ca. 1830.	SEDGWICK.	Elucidation of Devonian strata.
1830.	STEPHENSON.	Locomotive "Rocket" runs first railway journey, between Liverpool and Manchester.
1831.	LIEBIG.	(1803-1875) Discovers chloroform.
1832.	FARADAY.	Discovery of electromagnetic induction (foundation of dynamo).
1832.	WÖHLER AND LIEBIG.	Discover organic radicles.
1833.	FARADAY.	Discovers laws of electrolysis.
1833.	GAUSS AND WEBER.	First electric telegraph (at Göttingen).
1833.	GRAHAM.	Discovers rate of diffusion of gases.
1833.	LYELL.	"Principles of Geology" published.
1834.	DUMAS.	Discovers laws of substitution in organic chemistry.
1836.	DANIELL. GROVE.	Electric batteries invented, having their names.
1837.	AGASSIZ.	Discovers evidence of glacial age.
1837.	COOK. WHEATSTONE. MORSE.	Introduce telegraph by the use of electro-magnetism.
1837.	SCHWANN.	Discovers nature of fermentation.
1838.	BROWN.	Discovers the nucleus of plant cells and "Brownian motion."
1838.	MURCHISON.	Elucidation of Silurian strata.
1838.	SEDGWICK. MURCHISON.	Demonstration of main geological epochs.
1840.	LIEBIG.	Chemistry applied to physiology and agriculture.
1842.	DOPPLER.	Discovers displacement of spectral lines, with velocity of movement.
1842.	MAYER.	Mechanical equivalent of heat.
1843.	JOULE.	Demonstrates the conservation of energy, and discovers mechanical equivalent of heat.
1844.	VON MOHL.	Gives name *protoplasm* to living matter of cells.
1844.	SCHÖNBEIN.	Discovers ozone.
1846.	ADAMS. LEVERRIER.	Discover Neptune almost simultaneously.
1847.	HELMHOLTZ.	Formulates the first law of thermodynamics; propounds law of conservation of energy.

A.D.		
1847.	CLAUSIUS.	Second law of thermodynamics.
1847.	SIMPSON.	Uses chloroform as anæsthetic.
1847.	VON SOMBRERO.	Discovers nitroglycerine.
1849.	GRAHAM.	Discovers osmosis, by dialysis.
1850.	GRAHAM.	Diffusion of liquids.
1850.	HOFMEISTER.	Discovers the life cycle of cryptogamic plants, and demonstrates sexual function of cryptogams.
ca. 1850.	A. C. RAMSAY.	Elucidation of azoic (pre-Cambrian) formations.
ca. 1850.	SCHWABE.	Recognises sunspot cycle.
1850.	STOKES.	Discovers law of rate of fall of particles.
1851.	FIZEAU.	Determines velocity of light in moving water.
1852.	FRANKLAND.	Formulation of theory of valency in chemistry.
1852.	KELVIN (LORD).	Enunciates theory of dissipation of energy.
1853.	PASTEUR.	Researches on optically active tartaric acids.
1854.	AIRY.	Uses pendulum to weigh the earth; theory of isostasy in geology.
1856.	FUHLROTT.	Discovery of Neanderthal man.
1856.	W. H. PERKIN (SEN.).	Discovery of mauveine; and foundation of aniline dye industry.
1857.	BUYS BALLOT.	Relates wind direction to that of pressure (atmosphere).
1857.	CLAUSIUS.	Deduces kinetic theory of gases.
1857.	FARADAY.	Discovers "sols" and founds theory of colloid state.
1858.	CANNIZZARO.	Reinstates Avogadro's hypothesis and demonstrates difference between atoms and molecules.
1858.	PASTEUR.	Begins investigations on micro-organisms.
1858.	WALLACE.	Theory of evolution, simultaneously with Darwin.
1859.	BUNSEN AND KIRCHOFF.	Spectrum analysis introduced into chemistry.
1859.	CLERK MAXWELL.	Mathematical elucidation of kinetic theory of gases.
1859.	DARWIN.	"Origin of species" and theory of evolution.
1859.	DRAKE.	First boring for petroleum oil in Pennsylvania.
1860.	FRANKLAND. KOLBE. KEKULÉ.	Formulate fundamental theory of molecular structure in organic chemistry.
1860.	KIRCHOFF.	Law of emission and absorption of radiation.
1861.	GRAHAM.	Classic researches on colloids.
1862.	BERTHELOT.	Synthesis of acetylene.
1862.	PASTEUR.	Discovers microbic cause of fermentation.

A.D.		
1863.	Clerk Maxwell.	Propounds electromagnetic theory of light.
1863.	Huggins.	Photographs stellar spectra.
1863.	Huxley.	"Man's Place in Nature"; protagonist of evolution theory.
1863.	Pasteur.	Discovers bacillus of anthrax.
1864.	Newlands and Lothar Meyer.	Law of octaves (periodic law) among the elements.
1865.	Kekulé.	Propounds benzene theory (foundation of aromatic organic chemistry).
1865.	Lister.	Revolutionises hospital surgery by antiseptic treatment.
1865.	Mendel.	Discovers the laws of heredity.
1865.	Pasteur.	Proves microbes to be cause of disease infection.
1867.	Guldberg and Waage.	Fundamental law of "mass action" discovered in chemistry.
ca. 1867.	Langley.	Invents bolometer for measuring solar radiation.
1868.	Lockyer.	Discovers helium in sun.
1869.	Huggins.	Uses radiometer and other instruments in astronomy.
1869.	Mendeleef.	Classification of the elements by the periodic law.
1869.	Nobel.	Uses nitroglycerine as explosive.
1870.	Baeyer.	Theory of photosynthesis.
ca. 1870.	Bentham.	Classification of plant genera.
1870.	Willard Gibbs.	Mathematical examination of states (phases) of matter.
1870.	Liebig.	Discovery of invertase.
ca. 1872.	Stas.	Engaged in accurate atomic weight determinations.
1872.	van der Waals.	Equation of state for gases.
1873.		"Challenger" expedition (plankton).
1873.	Schneider. Flemming. Bütschli.	Discover chromosomes of cell-nuclei (name *chromosome* given by Waldeyer in 1888).
1874.	van 't Hoff. le Bel.	Discovery of stereo-isomerism (spacial arrangement of atoms in molecules).
ca. 1874 *et seq.*		Rise and development of modern organic chemistry.
1877.	Bell.	Invents the telephone.
1877.	Cailletet and Pictet.	Liquefaction of "permanent" gases.
1877.	Asaph Hall.	Discovers satellites of Mars.
1877.	Pasteur.	Founds "preventive medicine" (discovers vaccine for anthrax).
1877.	Pfeffer.	Discovers the semi-permeable membrane in osmosis.
ca. 1878 *et seq.*		Rise of modern bacteriology and scientific treatment of disease.
1878.	Baeyer.	Artificial synthesis of indigo.

A.D.		
ca. 1878.	WILLARD GIBBS.	Enunciation of phase-rule.
1879.	SIR WM. CROOKES.	Cathode rays and adumbration of theory of electrons.
1879.	EDISON AND SWAN.	Electric filament lamp invented.
1880.	DRAPER.	Photographs the Orion nebula.
ca. 1880.	LAPWORTH.	Traces zonal sequence of fossils in geological strata.
1880.	PASTEUR.	Founds serum therapy.
1881.	KELVIN (LORD).	Estimates the size of atoms.
1882.	KOCH.	Discovers consumption microbe (tubercle bacillus).
1882.	MICHELSON AND MORLEY.	Fail to find experimental evidence for drift through ether.
1882.	SCHIAPARELLI.	Investigates rotation of Mercury and Venus.
1883.	KOCH.	Discovers cholera bacillus.
1883.	RAOULT.	Law of freezing-point and molecular weight.
1885.	FITZGERALD.	Shows contraction with velocity.
1885.	WEISMANN.	Contests theory of inheritance of acquired characters.
1885.	BALMER.	Discovers formula for spectral line series.
1886.	VAN 'T HOFF.	Ionic theory of solution (electrolytic dissociation) and osmotic pressure.
1887.	ARRHENIUS.	
1887.	EMIL FISCHER.	Discovery of the spacial configuration of atoms in sugar molecules.
1887.	HERTZ.	Discovery of electric waves, and confirmation of electromagnetic theory of Maxwell.
1887.	VAN 'T HOFF.	Discovers laws of osmotic pressure.
1888.	HELBRIEGEL AND WILFURTH.	Discover nitrogen-fixing bacteria (*Bacillus radicicolus*).
1890.	BRANLY.	Invents "coherer" for "wireless."
1890.	WINOGRADSKY.	Discovery of nitrifying bacteria.
1891.	HALE.	Invents the spectro-heliograph.
1891.	WERNER.	Co-ordination valency theory.
1892.	DUBOIS.	Discovers ape-man fossil in Java (*Pithecanthropus erectus*).
1892.	METCHNIKOFF.	Discovers phagocytosis.
1893.	FINSEN.	Uses ultra-violet light in physiotherapy.
1894.	OLIVER LODGE. MARCONI.	First introduction of "wireless" messages.
1894.	WM. RAMSAY AND LORD RAYLEIGH.	Discovery of argon and helium.
ca. 1895.	LOCKYER.	Meteoritic hypothesis, with ascending and descending scale of stellar temperatures.
1895.	LORENTZ.	Postulates contraction of moving bodies.
1895.	RÖNTGEN.	Discovery of X-rays.
1895.	WILLIAMSON. SCOTT.	Demonstrate existence of "seed ferns" in carboniferous epoch.

A.D.		
1895.	Winogradsky.	Discovers nitrogen-fixing bacteria.
1896.	Boys.	Determines accurately density of earth.
1896.	Langley.	First aeroplane flight (steam driven).
1896.	Becquerel.	Discovery of radioactivity.
1896.	Zeeman.	Discovers the split of spectral lines by magnetic field.
1897.	Lowell.	Discloses properties of the planet Mercury.
1897.	J. J. Thomson.	Discovery of the electron and measurement of its charge.
1898.	Madame Curie.	Discovery of radium.
1898.	Ronald Ross. Manson.	Discovery of protozoal parasites in malarial infection.
1898.	Zsigmondy.	Examines nature of metallic "sols."
1900.	Larmor.	Publishes "Aether and Matter."
1900.	Planck.	Formulates quantum theory of radiation, and Planck's constant.
1900.	Wm. Ramsay.	Discovery of neon, krypton, and xenon in the atmosphere.
1900 *et seq.*		Rise and development of modern physical chemistry.
1901.	Emil Fischer.	Commences researches on constitution of proteins.
1901.	Takamine.	Isolates adrenalin from suprarenal gland.
1901.	de Vries.	Theory of mutation in biology.
1902.	de Bort.	Discovers stratosphere.
1902.	Heaviside.	Suggests ionised conducting layer in upper air.
1903.	Bayliss and Starling.	Discover secretin, and give name to *hormones*.
1903.	Rutherford.	Discovery of atomic disintegration of radioactive elements.
1903.	Rutherford. McLennan.	Discovery of cosmic rays; elucidation of β- and γ-rays.
1903.	C. T. R. Wilson.	Uses electrons as nuclei in condensation of water vapour.
1903.	Wilbur and Orville Wright.	First aeroplane flight (petrol driven).
1903.	Zsigmondy.	Invention of ultra-microscope and foundation of theory of colloids.
1904.	Rutherford and Wm. Ramsay.	Transmutation of radioactive elements proved, and α-particle identified with helium.
1904.	J. J. Thomson.	Propounds theory of electron-transfer in chemical combination.
1905.	Einstein.	Formulates "special principle" of relativity (space-time framework).

A.D.		
1905.	FLEMING.	Invents thermionic valve (electrons from hot filaments) in "wireless."
1905.	KAPTEYN.	Discovers existence of two distinct star drifts.
1905.	RUTHERFORD.	Determines speed of α- and β-particles in radioactivity.
1906.	PERRIN.	Determines Avogadro's constant and demonstrates the physical reality of molecules.
1906.	HOPKINS.	Suspects vitamins in food.
1907.	SCHOETENSACK.	Discovers Mauer jaw (of skull of Heidelberg man).
1908.	G. E. HALE.	Proves vortical nature of sun-spots by Zeeman effect.
1908.	WM. RAMSAY.	Formulates electronic theory of valency.
1908.	RUTHERFORD. RAMSAY AND GRAY.	Isolate niton (radon) and examine its physical constants.
1909.	PEARY.	Reaches North Pole.
1909.	WOLFGANG OSTWALD.	Founds modern theory of colloid state.
1911.	RUTHERFORD.	Founds modern theory of atomic structure.
1911.	AMUNDSEN.	Reaches South Pole (Dec.).
1912.	SCOTT.	Reaches South Pole (Jan.).
1912.	DAWSON.	Discovers Piltdown skull (*Eoanthropus*).
1912.	RUSSELL (SIR E. J.)	Traces "soil sickness" to protozoan destruction of bacteria.
1912.	HOPKINS.	Demonstrates the existence of vitamins in food.
1912.	LEAVITT (MISS).	Correlates cepheid brightness with period.
ca. 1912.	C. T. R. WILSON.	Elaborates method of tracking α-particles.
1913.	ASTON. SODDY.	Discovery of isotopes among the elements.
1913.	H. N. RUSSELL.	Classification of stars and first theory of stellar evolution.
1913.	SODDY.	Postulates fundamental nature of atomic number.
1913.	WIEN.	Enunciation of displacement law (energy and wave-length).
1913.	WILLSTÄTTER.	Elucidates the chemical nature of chlorophyll.
1914.	MOSELEY.	Discovers law fixing atomic number, by X-ray method.
1915.	BRAGG.	Devises new method of X-ray analysis (crystal structure).
1915.	EINSTEIN.	Formulates "general theory" of relativity and new theory of gravitation.
1915.	LOWELL.	Predicts trans-Neptunian planet.
1916.	BOHR AND RUTHERFORD.	Planetary theory of constitution of atoms developed.

A.D.		
1916.	G. N. LEWIS.	Develops electronic theory of valency.
1916.	NAPIER SHAW.	Cyclone theory (rotating discs).
ca. 1917.	BJERKNES (V. AND J.).	Cyclone theory (polar front).
1919.	EDDINGTON, ETC.	Verification of relativity prediction (light-bending) by solar eclipse.
1919.	RUTHERFORD.	Artificial transmutation of elements by bombarding with α-particles.
1919.	ASTON.	Invents mass spectrograph for measuring atomic mass of isotopes.
1920.	LANGMUIR.	Develops octet theory of electronic valency.
ca. 1920.	MICHELSON.	Measures diameter of giant stars by interferometer.
1920.	WEGENER.	Develops theory of floating continents.
1921.	BRAGG.	Elucidation of crystal-structure of solids by X-ray analysis.
1921.	GREGORY.	Estimates age of earth approximately correctly.
ca. 1921.	SHAPLEY.	Estimates distances of nebulæ and star clusters and size of Galaxy.
1922.	ASTON. RUTHERFORD.	Discovery of isobars and recognition of virtual truth of Prout's hypothesis.
1922.	BANTING.	Discovery of use of insulin in diabetes.
1922.	EDDINGTON.	Investigates nature of energy-generation in stars.
1923.	JOLY.	Connects earth's crustal movements with radioactivity.
1923.	G. C. SIMPSON.	Fundamental physics of atmosphere in relation to meteorology.
1923.	A. V. HILL.	Chemical physiology of muscle contraction.
1923.	COMPTON.	"Effect" with scattered radiation, and corpuscular nature of X-rays.
1924.	DE BROGLIE.	New theory of wave mechanics.
1924.	JEANS.	Theory of origin of solar system.
1925.	HEISENBERG. DIRAC. SCHRÖDINGER.	New quantum theory and wave mechanics first developed; indeterminacy principle.
1925.	HUBBLE.	Estimates the number of nebulæ in visible universe.
1925.	JEANS.	Theory of annihilation of stellar matter.
1925.	RAYMOND DART.	Discovery of Taungs skull.
1925.	KAMMERER.	Asserts inheritance of some acquired characters (in toads)

A.D.		
1925.	MILLIKAN.	Proves origin of cosmic rays.
1925.	H. N. RUSSELL.	Formulates new theory of annihilation of matter in stars at high temperatures.
1926.	EDDINGTON.	Radiation - pressure theory of stellar origins.
1927.	HARINGTON AND BARGER.	Synthesise thyroxin (principle of thyroid gland).
1927.	HAWORTH.	Elucidation of constitution of the complex carbohydrates.
1927.	RAMAN.	Discovers law of frequency-difference in scattered radiation.
1927.	WILLSTATTER.	Investigations on nature of enzymes.
1928.	JEANS.	Theory of "liquid" stars.
1928.	DE SITTER.	New theory of universal time and space.
1929.	ASTON.	Discovery of "packing fraction" in genesis of elements.
1929.	JEANS.	Mathematical elucidation of the universe; modern cosmogony.
1929.	RUTHERFORD.	Constitution of atomic nuclei.
1929.	G. C. SIMPSON.	Formulates theory explaining glacial epochs.
1929.	PEI.	Discovers skull of early ape-man (*Sinanthropus*) in China.
1929.	ENSTEIN.	"Unified field" theory of gravitation and electromagnetism.
1930.	SHAPLEY. TOMBAUGH.	Discovery of supposed trans-Neptunian planet (Pluto).

To Illustrate Time Intervals in History of Earth.

N.B.—Times given are only very rough approximations.

Era	Subdivision	Reduce a Million Year Interval to One Year.			Chief Event.	
Cainozoic.	Neo-gene.	Recent period becomes ..	4	weeks.	Aurignacian man, Stone Age and civilisation.	Age of mammals.
		Pleistocene period becomes ..	22	,,	Primitive man appears. Old Stone Age.	
		Pliocene period becomes ..	6	months.	Pithecanthropus (ape-man) at close of period.	
		Miocene period becomes ..	12	,,	Himalayan mountain barrier rises.	
	Palæo-gene.	Oligocene period becomes ..	6	,,	Tail-less anthropoids (catarrhine apes) appear.	
		Eocene period becomes ..	10	years.	First primates (ape stock).	
Meso-zoic		Cretaceous period becomes ..	15	,,	Mammals displacing reptiles.	
		Jurassic period becomes ..	30	,,	True mammals appear; also primitive birds.	Age of giant reptiles.
		Triassic period becomes ..	18	,,	Primitive small pro-mammals appear.	
Palæozoic		Permian period becomes ..	11	,,	Reptiles abundant.	
		Carboniferous period becomes	46	,,	Amphibians and insects first appear; later pro-reptiles. Land vegetation abundant.	
		Devonian period becomes ..	23	,,	Pro-amphibians (dipneusts) appear. First air-breathing animals and plants.	
		Silurian period becomes ..	34	,,	Fishes (primitive forms) first appear.	Life confined to the sea.
		Ordovician period becomes ..	48	,,	Graptolites and trilobites abundant.	
		Cambrian period becomes ..	42	,,	Invertebrate animals first appear (crustaceans, molluscs, vermes, etc.).	
		Total about	280	,,		
Pre-Cambrian or Archæan, say			320	,,	Low forms of life appear (protista) in latest formations (Torridonian, etc.).	
Period of warm ocean and cloud-capped atmosphere, say			400	,,		
Period of general cooling, say ..			2,000	,,		
		Total, say	3,000	,,		

TO ILLUSTRATE PRINCIPAL EVENTS IN ARCHÆOLOGY (EUROPE).

N.B.—Max.=maximum. This table is best read from bottom upwards, but dates are only provisional and conjectural.

	Years Ago.	Climate of Europe.	Stage of Human Development.	Culture.	
Recent.	Today	Max. of long interglacial period (genial).	Modern civilisation.	Science and engineering.	Iron Age.
	300-400	Genial.	,, ,,	Max. phase of art (modern period).	
	2,200	,,	Classic civilisation (S. and E.) Barbarian civilisation (N. & W.)	Max. phase of Hellenic art.	
	2,700	,,	Beginning of Classic period.	Beginning of Iron Age.	
	3,400	,,	Late Minoan civilisation.	Max. phase of art (Mycenæan).	Bronze Age.
	4,400	,,	Middle Cretan(Minoan)civilisation.	Beginning of Bronze Age.	
	10,000	Colder than at present.	Daun period (nascent civilisation).	High-class stone implements. Agriculture, domestication of animals and plants. Clothes; villages of huts and lake dwellings.	Neolithic.
	15,000	Last retreat of ice, and change to warmer climate.	Azilian-Tardenoisean culture.	High-class stone tools. No art. Hut and pit dwellings. "Kitchen middens," remains of dog and shell-fish.	Mesolithic
	22,000	Cold set-back (Bühl) after Würm glaciation.	Magdalenian culture.	Cave and hut dwellings. Art rapidly flourishing. Religious and magical rites.	Upper Palæolithic.
	50,000	Milder, but cold.	Solutrian culture.	Hunters and fishers; sculpture, pottery, engraving and painting on cave walls, etc.; skilled tools in stone. Poor art	
	70,000	Very cold. Ice retreating.	Aurignacian and Cro-Magnon (Neo-Anthropic race invasion).	Skilled tools in horn, etc.; pictorial art. Extermination of Mousterian aborigines.	

Pleistrocene period.	90,000	Max. of Würm glacial period (last).*	Aurignacian man first appears.	Reindeer hunters; magnificient physique, modern type.	Middle Palæolithic.
	100,000	Very cold, wretched climate.	Neanderthal man.	Mousterian culture. No art; degeneration of flint tools. Hunters. Religion; fire known. Essentially cave-dwellers.	
	120,000	Max. of short interglacial period (warm and wet).	Acheulean period.	Culture perhaps lower than modern savages. High-class stone tools.	Lower Palæolithic.
	150,000	Max. of Riss glacial period.			
	200,000	Cold.	End of Chellean period.	Hunters, lived in open and in huts of boughs or hides. Savage but human; could make fire; sub-tropical fauna at first.	
	230,000	Very warm (forest conditions).	Chellean period.		
Pleistocene period.	250,000	Max. of long interglacial period (genial and dry).	*Homo sapiens* (no known skeletal remains).	? Pre-Chellean period. Hunters, living in open and in huts. Fire apparently known.	
	340,000	Max. of Mindel glacial period.			
	380,000	Max. of short interglacial period (warm and wet).	Primitive man (*H. Heidelbergensis*).	Beginning of Stone Age	
	400,000	Cold.	Primitive man (*Eoanthropus*) of Piltdown, Sussex.	Human type of skull. First primitive tools. ? Beginnings of speech.	
	410,000	Max. of Günz glacial period.			
	500,000		*Pithecanthropus erectus* of Java (ape-man).	Erect posture, ape skull; human affinities.	

* During max. of glaciation, the ice sheet was continuous, north of Lat. 52°; south of this, in patches (uplands and mountain areas). England was connected with European continent probably until the Mesolithic period.

INDEX

NOTE.—*The names of individuals are printed in heavier type throughout the Index. The latter contains no page references to entries in the Chronological Table* (*pp.* 467-482), *which, however, includes some historical items not dealt with in the text of the book.*

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